

**ANALISIS INTRUKSIONAL
GARIS-GARIS BESAR PROGRAM PENGAJARAN
RENCANA EVALUASI PROSES BELAJAR MENGAJAR
BAHAN AJAR**

**FISIKA STATISTIKA
D1C324
BOBOT: 3 SKS**



**PENGAJAR : I MADE JONI, S.Si, M.Sc
NIP : 132 296 651
SEMESTER : V (LIMA)**

**JURUSAN FISIKA
FAKULTAS MATEMATIKA DAN ILMU PENGETAHUAN ALAM
UNIVERSITAS PADJADJARAN
ANGKATAN XXI
2006**

LEMBAR PENGESAHAN

JUDUL : ANALISIS INTRSUKSIONAL, GARIS-GARIS BESAR
PROGRAM PENGAJARAN, RENCANA EVALUASI
PROSES BELAJAR MENGAJAR , DAN BAHAN AJAR

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Bandung, Maret 2006

**Pembimbing,
TIM INTI PEKERTI/AA
UNIVERSITAS PADJADJARAN BANDUNG**

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Mengetahui/menyetujui

**Dekan
Fakultas Matematika dan Ilmu Pengetahuan Alam**

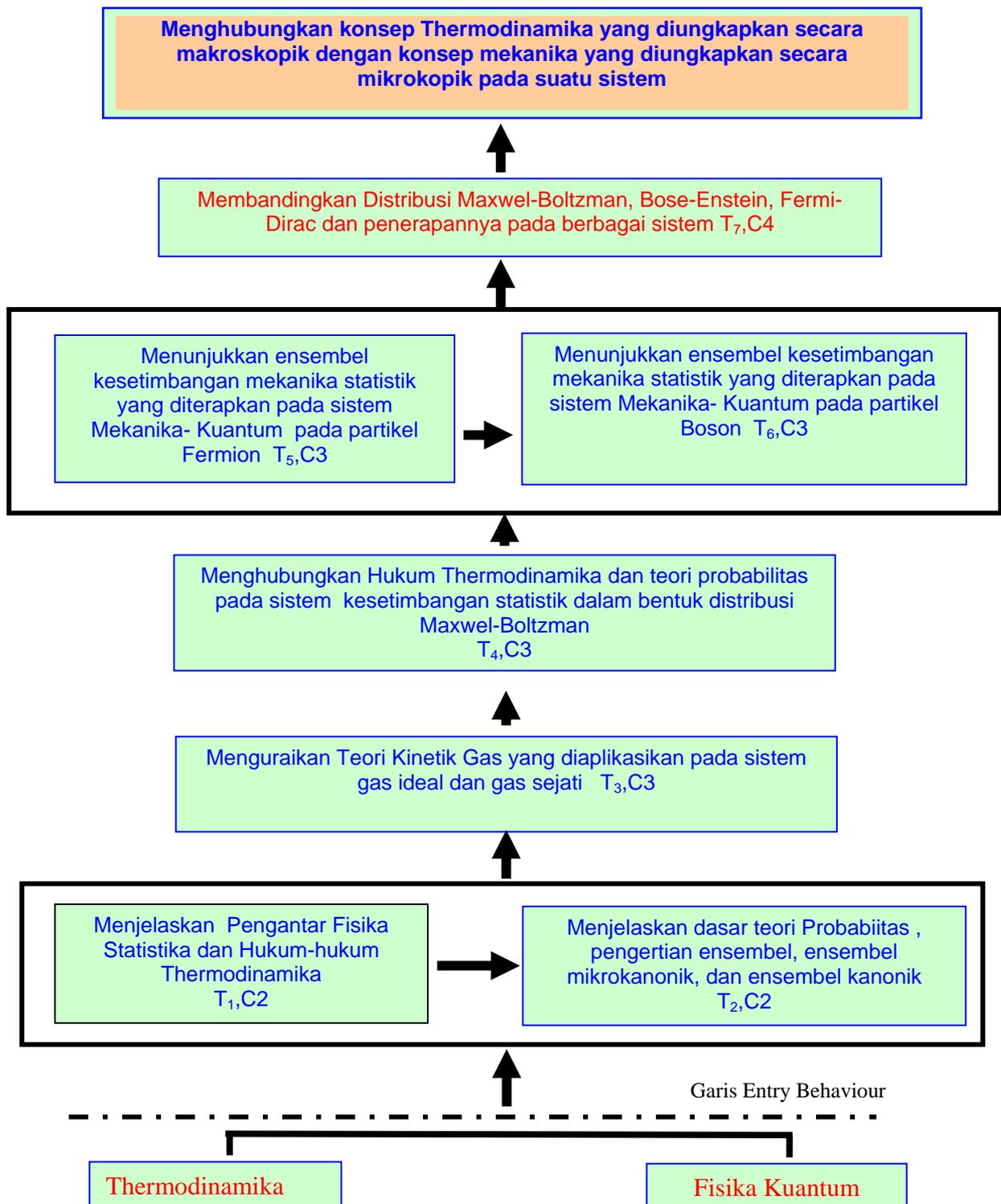
**Ketua P3AI
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**Prof. Dr. Husein H. Bahti
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NIP 130 354 298**

1. ANALISIS INSTRUKSIONAL

MATA KULIAH FISIKA STATISTIKA



Keterangan:

T_1 - T_7 adalah pelabelan untuk objektif dalam tabel taksonomi

C_2 - C_4 adalah ranah kognitif; C_2 : Pemahaman C_3 : Penerapan; C_4 : Analisis

2. GARIS-GARIS BESAR PROGRAM PENGAJARAN

GARIS-GARIS BESAR PROGRAM PENGAJARAN (GBPP)

MATA KULIAH : **FISIKA STATISTIKA**
KODE MATA KULIAH : **D1C234**
KREDIT : **3 (3 - 0)**
SEMESTER : **V (LIMA)**
PENANGGUNG JAWAB : **I MADE JONI, S.Si, M.Sc./ 132 296 651**
MATA KULIAH

DESKRIPSI SINGKAT : Mata Kuliah Fisika Statistik merupakan Mata Kuliah yang membahas hubungan makroskopis dari sifat-sifat Termodinamika suatu material dengan ungkapan secara mikroskopik menggunakan teori dinamika partiel yang dikandung suatu atom atau molekul baik secara klasik maupun kuantum.

TUJUAN INSTRUKSIONAL UMUM (TIU):

Setelah mengikuti mata kuliah Fisika Statistika, mahasiswa akan dapat menghubungkan konsep termodinamika yang diungkapkan secara makroskopik dengan konsep mekanika yang diungkapkan secara mikroskopik pada suatu sistem.

NO	TUJUAN INSTRUKSIONAL KHUSUS	POKOK BAHASAN DALAM MATA PELAJARAN	SUB POKOK BAHASAN	MOTODE	MEDIA	WAKTU (menit)	DAFTAR PUSTAKA
1	2	3	4	5	6	7	8
I	Setelah mengikuti perkuliahan dengan pokok bahasan <i>Pengantar Fisika Statistika</i> dan <i>Pembahasan Ulang Hukum-Hukum Termodinamika</i> ini, Mahasiswa akan dapat menjelaskan posisi mata kuliah Fisika Statistika dan kaitannya dengan Hukum-Hukum Termodinamika secara benar. (T1,C2)	Pengantar Fisika Statistika dan Pembahasan Ulang Hukum-Hukum Termodinamika	Pengantar Fisika Statistika Hukum Termodinamika ke nol Hukum Termodinamika ke satu Hukum Termodinamika ke dua Hukum Termodinamika ke tiga Kesetimbangan Termodinamika	Ceramah & Tanya Jawab	Infocus dan Whiteboard	10 20 20 50 30 20	BW1, BW3, BW5, BA3-10
						150	

NO	TUJUAN INSTRUKSIONAL KHUSUS	POKOK BAHASAN DALAM MATA PELAJARAN	SUB POKOK BAHASAN	MOTODE	MEDIA	WAKTU (menit)	DAFTAR PUSTAKA
1	2	3	4	5	6	7	8
II	Setelah mengikuti perkuliahan dengan pokok bahasan <i>Teori Probabilitas</i> dan <i>Sistem Termodinamika</i> , Mahasiswa akan dapat menjelaskan teori probabilitas dan tipe-tipe sistem yang ada pada sistem termodinamika dengan benar. (T2,C2)	Teori Probabilitas dan Sistem Termodinamika	Teori Probabilitas dan Informasi (Konsep Entropy	Ceramah & Tanya Jawab	Infocus dan Whiteboard	50	BW3 , BW5 , BA6-8
			Ensembel Mikrokanonik			50	
			Ensembel Kanonik			50	
						150	
III	Setelah mengikuti perkuliahan dengan pokok bahasan Teori Kinetik Gas ini, Mahasiswa akan dapat menguraikan Teori Kinetik Gas yang diaplikasikan pada sistem gas ideal dan gas sejati dengan benar. (T3,C3)	Teori Kinetik Gas	Tekanan Gas	Ceramah & Tanya Jawab	Infocus dan Whiteboard	20	BW3 , BW4 , BA1-7
			Kompresibilitas Gas			30	
			Temperatur dan Energi Kinetik			50	
			Hukum Gas Ideal			30	
			Persamaan Keadaan Gas Ideal			20	
			Kapasitas Panas Gas Ideal Monoatomik dan Polyatomik			100	
			Hukum Gas Sejati			50	
						300	

NO	TUJUAN INSTUKSIONAL KHUSUS	POKOK BAHASAN DALAM MATA PELAJARAN	SUB POKOK BAHASAN	MOTODE	MEDIA	WAKTU (menit)	DAFTAR PUSTAKA
1	2	3	4	5	6	7	8
IV	Setelah mengikuti perkuliahan dengan pokok bahasan <i>Distribusi Statistika Maxwell-Boltzman</i> , Mahasiswa akan dapat menghubungkan Hukum-hukum Termodinamika dan teori probabilitas pada sistem kesetimbangan statistika dalam pandangan kalsik dengan benar dengan benar(T4,C3)	Distribusi Statistika Maxwell-Boltzman	Kesetimbangan Statistika Hukum Distribusi Maxwell-Boltzman Distribusi M-B dalam ungkapan Temperatur Distribusi Kecepatan M-B Aplikasi distribusi M-B pada Gas Ideal Fungsi Partisi Enegi Dalam Energi Bebas Helmholtz Tekanan pada gas ideal klasik Prinsip Ekuipartisi Energi Paradok Gibbs Persamaan Sackur-Tetrode Hukum Thermodinamika dalam sudut pandang mekanika statsitik (Hukum Thermodinamika I,II,III)	Ceramah & Tanya Jawab	Infocus dan Whiteboard	20 30 50 50 50 30 20 20 30 30 50 20 50	BW1-5, BA6-8
						450	

NO	TUJUAN INSTUKSIONAL KHUSUS	POKOK BAHASAN DALAM MATA PELAJARAN	SUB POKOK BAHASAN	MOTODE	MEDIA	WAKTU (menit)	DAFTAR PUSTAKA
1	2	3	4	5	6	7	8
V	Setelah mengikuti perkuliahan dengan pokok bahasan <i>Distribusi Statistika Fermi-Dirac</i> ini, Mahasiswa akan dapat menunjukkan ensembel kesetimbangan mekanika statistika yang diterapkan pada sistem Mekanika-Kuantum pada partikel Fermion dengan benar (T5,C3)	Distribusi Statistika Fermi-Dirac	Statistika Fermi Dirac	Cearamah & Tanya Jawab	Infocus dan Whiteboard	100	BW1-5, BA1-10
			Aplikasi pada Gas Ideal Fermi (gas electron) dan Sifat Logam			100	
			Aplikasi Distribusi F-D pada Semikonduktor dan Ferromagnetik			100	
						300	
VI	Setelah mengikuti perkuliahan dengan pokok bahasan <i>Distribusi Statistika Bose-Enstein</i> ini, Mahasiswa akan dapat menunjukkan ensembel kesetimbangan mekanika statistika yang diterapkan pada sistem Mekanika-Kuantum pada partikel Boson dengan benar. (T6, C3)	Distribusi Statistika Bose-Enstein	Statistika Bose Enstein	Caramah & Tanya Jawab	Infocus dan Whiteboard	100	BW1-5, BA6
			Aplikasi Stat. B-E pada Gas Ideal Bose (Gas Photon) dan Sifat-sifat Radiasi Benda Hitam			100	
			Aplikasi Dist. B-E pada LASER			100	
						300	

NO	TUJUAN INSTUKSIONAL KHUSUS	POKOK BAHASAN DALAM MATA PELAJARAN	SUB POKOK BAHASAN	MOTODE	MEDIA	WAKTU (menit)	DAFTAR PUSTAKA
1	2	3	4	5	6	7	8
VII	Setelah mengikuti perkuliahan dengan pokok bahasan <i>Perbandingan Distribusi Statistika dan Penerapannya</i> , Mahasiswa akan dapat membandingkan Distribusi Maxwel-Boltzman, Bose-Einstein, Fermi-Dirac dan penerapannya pada berbagai sistem dengan benar (T7,C4)	Perbandingan Distribusi Statistika dan Penerapannya	Perbandingan distribusi M=B, B-E, dan F-D	Ceramah & Tanya Jawab	Infocus dan Whiteboard	50	BW1-4, BA 1-13
Penerapan distribusi Fermi dirac pada Fisika Keuangan			50				
Presentasi Makalah penerapan distribusi statistika			350				
						450	
Total waktu selama satu semester (Menit)						2100	

DAFTAR PUSTAKA
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BUKU/BACAAN ANJURAN (BA)

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- 5 <http://newton.ex.ac.uk/handbook/modules/PHY1002.html>
- 6 http://newton.ex.ac.uk/teaching/rj/stat_2003_notes.pdf
- 7 http://newton.ex.ac.uk/teaching/rj/prob_stat_03.pdf
- 8 <http://www.dur.ac.uk/~dph0pdh/StatP.html>
- 9 <http://www.sussex.ac.uk/physisc/teaching/mgb/statisticalPhysics/>
- 10 <http://www.uio.no/yurig>
- 11 <http://newton.ex.ac.uk/handbook/modules/book-list.html#MANDL>
- 12 <http://newton.ex.ac.uk/handbook/modules/book-list.html#BOWLEY>
- 13 <http://newton.ex.ac.uk/teaching/rj>

3. RENCANA EVALUASI PROSES BELAJAR MENGAJAR

3.1. RENCANA EVALUASI

MATA KULIAH : **FISIKA STATISTIKA**
KODE MATA KULIAH : **D1C 324**
KREDIT : **3 (3 - 0)**
SEMESTER : **V (LIMA)**
PENANGGUNG JAWAB : **I MADE JONI, S.Si, M.Sc./ 132 296 651**
MATA KULIAH
JURUSAN/FAKULTAS : **FISIKA/ FMIPA**

WAKTU PELAKSANAAN :

TUJUAN EVALUASI:

1. Mendapatkan umpan balik dari mahasiswa dan rekan dosen terhadap kualitas materi perkuliahan yang diberikan selama PBM
2. Mengetahui bagaimana pendapat mahasiswa tentang strategi PBM yang digunakan
3. Mengetahui bagaimana persepsi mahasiswa terhadap kemampuan dosen dalam menyelenggarakan PBM
4. Mengetahui pendapat mahasiswa dan rekan-rekan dosen apakah sarana perkuliahan memadai dan apakah sarana yang ada sudah dipergunakan secara optimal

Tabel Rencana Evaluasi PBM

NO	INFORMASI YANG DIBUTUHKAN	INDIKATOR		METODE/ TEKNIK	INSTRUMENT	RESPONDEN	WAKTU
1	2	3		4	5	6	7
1	Mendapatkan umpan balik dari mahasiswa terhadap materi perkuliahan yang diberikan selama PBM	1	Kemutahiran bahan-bahan	Review Dokumen	Pedoman Review Dokumen	Rekan dosen	Setelah UTS
				Kuesioner	Pedoman Kuesoner	Mahasiswa	Setelah UTS
		2	Pemberian informasi buku referensi utama dengan jelas	Kuesioner	Pedoman Kuesoner	Mahasiswa	Setelah UTS
		3	Penyampaian silabus atau kontrak perkuliahan sebelum perkuliahan dimulai	Kuesioner	Pedoman Kuesoner	Mahasiswa	Setelah UTS
		4	Pembuat catatan kuliah/hand out	Kuesioner	Pedoman Kuesoner	Mahasiswa	Setelah UTS
		5	Penyajian slide kuliah dengan power point	Kuesioner	Pedoman Kuesoner	Mahasiswa	Setelah UTS
		6	Sistematika dan cakupan materi	Review Dokumen	Pedoman Review Dokumen	Rekan dosen	Setelah UTS
				Kuesioner	Pedoman Kuesoner	Mahasiswa	Setelah UTS
		8	Kesesuaian materi/desain GBPP dengan silabus/kurikulum	Review Dokumen	Pedoman Review Dokumen	Dosen ynag bersangkutan dan Rekan dosen	Akhir Semester
		9	Kesesuaian kualitas tugas dan ujian terhadap pencapain ranah kognitif yang diharapkan	Analisis soal dan hasil ujian	Pedoman Review Dokumen	Dosen ynag bersangkutan dan Rekan dosen	Akhir Semester
		10	Kesesuaian tugas dan ujian terhadap materi kuliah yang diberikan	Kuesioner	Pedoman Kuesoner	Mahasiswa	Akhir Semseter
11	Kesesuaian materi perkuliahan dengan silabus pada kontrak perkuiahan	Kuesioner	Pedoman Kuesoner	Mahasiswa	Akhir Semseter		

NO	INFORMASI YANG DIBUTUHKAN	INDIKATOR	METODE/ TEKNIK	INSTRUMENT	RESPONDEN	WAKTU	
1	2	3	4	5	6	7	
2	Mengetahui bagaimana pendapat mahasiswa tentang strategi PBM yang digunakan	1	Keefektifan strategi perkuliahan ceramah & Tanya Jawab yang digunakan	Kuesioner	Pedoman Kuesioner	Mahasiswa	Setelah UTS
		2	Keefektifan strategi tugas pembuatan makalah untuk meningkatkan kemampuan mahasiswa dalam mencari informasi dan kemampuan teknik menulis.	Kuesioner	Pedoman Kuesioner	Mahasiswa	Akhir Semseter
		3	Keefektifan tugas makalah dalam bentuk kelompok untuk meningkatkan kemampuan mahasiswa bekerjasama dalam tim	Kuesioner	Pedoman Kuesioner	Mahasiswa	Akhir Semseter
		4	Keefektifan penugasan presentasi makalah yang diberikan untuk meningkatkan kemampuan berbicara dan berdiskusi mahasiswa.	Kuesioner	Pedoman Kuesioner	Mahasiswa	Akhir Semseter
3	Mengetahui persepsi mahasiswa terhadap kemampuan dosen dalam menyelenggarakan PBM	1	Penguasaan dosen terhadap materi kuliah Kemampuan menjelaskan	Kuesioner	Pedoman Kuesioner	Mahasiswa	Setelah UTS
		2	Kemampuan dosen dalam berdialog dengan mahasiswa	Kuesioner	Pedoman Kuesioner	Mahasiswa	Setelah UTS
		3	Kemampuan dosen dalam memotivasi mahasiswa	Kuesioner	Pedoman Kuesioner	Mahasiswa	Setelah UTS
		3	Kemampuan dosen dalam mengaitkan perkuliahan dengan dengan perkuliahan lain	Kuesioner	Pedoman Kuesioner	Mahasiswa	Setelah UTS
		4	Ketersediaan waktu dosen untuk konsultasi di luar waktu tatap muka di kelas	Kuesioner	Pedoman Kuesioner	Mahasiswa	Setelah UTS

NO	INFORMASI YANG DIBUTUHKAN	INDIKATOR		METODE/ TEKNIK	INSTRUMENT	RESPONDEN	WAKTU
1	2	3		4	5	6	7
4	Mengetahui pendapat mahasiswa dan rekan-rekan dosen apakah sarana perkuliahan memadai dan apakah sarana yang ada sudah dipergunakan secara optimal	1	Penggunaan sarana yang ada dengan optimal	Review Dokumen	Pedoman Review Dokumen	Rekan dosen	Setelah UTS
				Kuesioner	Pedoman Kuesoner	Mahasiswa	
		2	Ketersediaan buku-buku referensi di perpustakaan	Review Dokumen	Pedoman Review Dokumen	Rekan dosen	Setelah UTS
				Kuesioner	Pedoman Kuesoner	Mahasiswa	Setelah UTS

3.2. DESAIN FORM KUESIONER DAN INTERVIEW UNTUK MAHASISWA

**EVALUASI PROGRAM PERKULIAHAN
JURUSAN FISIKA
FAKULTAS MATEMATIKA DAN ILMU PENGETAHUAN ALAM
UNIVERSITAS PADJADJARAN
(Diisi oleh mahasiswa)**

Kuisisioner ini dimaksudkan untuk mengumpulkan informasi mengenai cara mengajar dosen dalam perkuliahan yang anda ikuti di Jurusan Fisika FMIPA, Unpad. Hasil dari kuisisioner ini akan dijadikan salah satu acuan untuk peningkatan proses belajar mengajar di Jurusan Fisika, FMIPA, Unpad.

Petunjuk:

Anda diminta untuk mengisi kuisisioner di bawah ini dan memberi tanda silang (X) pada kolom yang sesuai dengan kriteria penilaian anda.

Kriteria penilaian sesuai dengan skala:

1 = Sangat tidak setuju; 2 = Tidak setuju; 3 = Setuju; 4 = Sangat setuju

MATA KULIAH : ...FISIKA STATISTIKA

DOSEN :I MADE JONI, S.Si, M.Sc.....

TANGGAL PENGAMBILAN DATA : 28-10-2006.....

A. FORM KUESIONER

Dalam menyajikan kuliah, dosen :		1	2	3	4
Mendapatkan umpan balik dari mahasiswa terhadap materi perkuliahan yang diberikan selama PBM					
1.	menggunakan bahan bacaan edisi baru (dari tahun 2000)				
2.	memberikan informasi buku referensi utama dengan jelas				
3.	menyampaikan silabus sebelum perkuliahan dimulai				

4.	membuat catatan kuliah/hand out				
5.	menyajikan kuliah dengan ppt				
6.	menjelaskan pokok bahasan yang akan diajarkan pada awal perkuliahan				
7.	menjelaskan relevansi mata kuliah yang diajarkan dengan mata kuliah lain yang terkait				
8.	Kesesuaian materi perkuliahan dengan silabus pada kontrak perkuliahan				
9.	memberikan standar penilaian yang jelas				
10.	memberikan tugas dan latihan sesuai dengan topik yang diajarkan				
11.	memberikan tugas/latihan yang dapat mendorong mahasiswa berfikir				
12.	memberikan soal uts/uas sesuai dengan materi yang diajarkan				
13.	memberikan solusi usa/uts setelah ujian ybs dilaksanakan				
14.	memeriksa serapan mahasiswa terhadap materi yang telah diajarkan melalui quiz				
15.	Memberikan tugas yang relevan dengan mata kuliah yang diajarkan				
16.	Memberikan soal-soal UTS dan UAS sesuai dengan materi yang diajarkan				
Mengetahui bagaimana pendapat mahasiswa tentang strategi PBM yang digunakan					
17	Keefektifan strategi perkuliahan ceramah &Tanya Jawab yang digunakan				
18	Kefektifan strategi tugas pembuatan makalah untuk meningkatkan kemampuan mahasiswa dalam mencari informasi dan kemampuan teknik menulis.				
19	Keefektifan tugas makalah dalam bentuk kelompok untuk meningkatkan kemampuan mahasiswa bekerjasama dalam tim/kelompok (team work)				
20	Keefektifan penugasan presentasi makalah yang diberikan untuk meningkatkan kemampuan berbicara dan berdiskusi mahasiswa.				
Mengetahui persepsi mahasiswa terhadap kemampuan dosen dalam menyelenggarakan PBM					
21.	menjawab pertanyaan mahasiswa dengan baik				
22.	menerangkan materi kuliah dengan jelas				
23.	mengajar dengan tahapan-tahapan yang mudah diikuti				
24.	menggunakan contoh yang menarik dalam menjelaskan sesuatu				
25.	mempertajam kemampuan mahasiswa dalam menjawab dan menyelesaikan soal				
26.	mendorong mahasiswa terlibat (bertanya, menjawab pertanyaan, dsb) dalam perkuliahan				

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Tuliskan hal-hal penting mengenai proses belajar mengajar mata kuliah ini yang perlu ditingkatkan dan mengapa perubahan tersebut perlu dilakukan?

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Terima kasih atas kerja sama Anda. Masukan Anda dalam Kuesioner ini sangat membantu dalam meningkatkan layanan proses belajar mengajar.

3.3. CONTOH HASIL DAN ANALISIS EVALUASI KUESIONER MAHASISWA

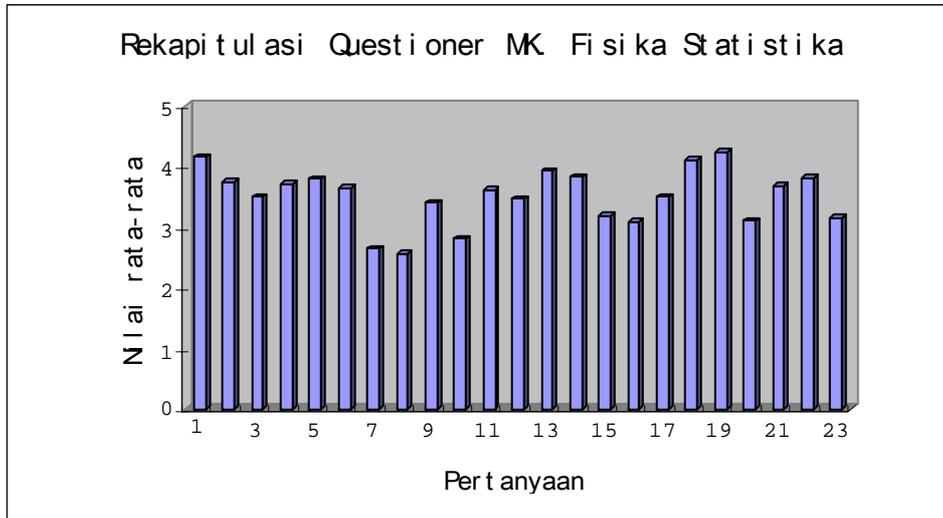
Berikut ini adalah contoh hasil evaluasi mata kuliah Fisika Statistika:

**CONTOH HASIL REKAPITULASI KUESIONER MAHASISWA PESERTA
MATA KULIAH FISIKA STATISTIKA
SEMESTER GANJIL TAHUN 2005-2006
PENGAJAR: I MADE JONI, M.Sc.
JUMLAH RESPONDEN: 53 ORANG**

No	Uraian	Penilaian Responden					Jumlah Responden	Nilai rata-rata
		1	2	3	4	5		
1	Memberikan silabus sebelum perkuliahan dimulai	0	1	3	35	14	53	4.15
2	Memberikan standar penilaian yang jelas	0	4	9	32	8	53	3.75
3	Memberikan informasi buku referensi utama dengan jelas	0	6	15	24	7	52	3.50
4	Menjelaskan pokok bahasan yang akan diajarkan pada awal perkuliahan	0	2	15	30	6	53	3.72
5	Menjelaskan relevansi mata kuliah yang diajarkan dengan mata kuliah lain yang terkait	0	2	9	38	4	53	3.79
6	Menyajikan materi kuliah sesuai dengan silabus yang diberikan	0	3	13	34	3	53	3.64
7	Menerangkan materi kuliah dengan jelas	3	12	28	9	1	53	2.64
8	Mengajar dengan tahapan-tahapan yang mudah diikuti	0	16	28	9	0	53	2.57
9	Menggunakan contoh yang menarik dalam menjelaskan sesuatu	0	3	26	21	3	53	3.40
10	Mempertajam kemampuan mahasiswa dalam menjawab dan menyelesaikan soal	1	9	33	10	0	53	2.81
11	Mendorong mahasiswa terlibat (bertanya, menjawab pertanyaan dsb) dalam perkuliahan	0	3	16	28	5	52	3.62
12	Menjawab pertanyaan mahasiswa dengan baik	0	4	20	25	4	53	3.47
13	Memberikan tugas yang relevan dengan mata kuliah yang diajarkan	0	2	5	39	7	53	3.92
14	Membina kemampuan mahasiswa untuk bekerja dalam <i>team work</i>	1	1	11	32	8	53	3.83
15	Memberikan kesimpulan tentang pokok-pokok perkuliahan yang telah diajarkan	0	6	26	20	1	53	3.19
16	Memeriksa serapan mahasiswa terhadap materi yang diajarkan melalui quiz	1	9	18	25	0	53	3.09
17	Memberikan soal-soal UTS dan UAS sesuai dengan materi yang diajarkan	0	4	16	31	2	53	3.51
18	Menggunakan fasilitas proses belajar mengajar di kelas secara optimal	0	2	3	33	15	53	4.11
19	Hadir dalam waktu perkuliahan rata-rata di atas 80%	0	1	3	30	19	53	4.25
20	Mengganti waktu kuliah apabila berhalangan hadir	1	8	23	16	4	52	3.12
21	Hadir tepat waktu (tidak terlambat)	0	2	17	28	6	53	3.68
22	Membuat catatan kuliah/handout	0	4	6	35	8	53	3.81
23	Secara keseluruhan saya puas dengan perkuliahan ini	0	7	24	22	0	53	3.15
Nilai rata-rata total								3.51

Keterangan skala penilaian:

- 1 = sangat tidak setuju
- 2 = tidak setuju
- 3 = netral
- 4 = setuju
- 5 = sangat setuju

ANALISIS HASIL EVALUASI DARI KOESIONER MAHASISWA

4. BAHAN AJAR

Lecture Note On Statistical Physics





James Clerk Maxwell



Probability that energy state E is occupied

BE

MB

FD with $E_F \cong 2.0 \text{ eV}$

all $\propto e^{-E/k_b T}$

$E \text{ (eV)}$



The Nobel Prize in Physics 1933

"for the discovery of new productive forms of atomic theory"



Erwin Schrödinger

1/2 of the prize

Austria

Berlin University
Berlin, Germany

b. 1887
d. 1961



Paul Adrien Maurice Dirac

1/2 of the prize

United Kingdom

University of Cambridge
Cambridge, United Kingdom

b. 1902
d. 1984



The Nobel Prize in Physics 1921

"for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect"



Albert Einstein

Germany and Switzerland

Kaiser-Wilhelm-Institut (now Max-Planck-Institut) für Physik
Berlin, Germany

b. 1879
(in Ulm, Germany)
d. 1955



S. N. Bose

$$f_{MB} = Ae^{-E/kT}$$

$$f_{BE} = \frac{1}{e^{E/kT} - 1}$$

$$f_{FD} = \frac{1}{e^{(E-E_F)/kT} + 1}$$



The Nobel Prize in Physics 1938

"for his demonstrations of the existence of new radioactive elements produced by neutron irradiation, and for his related discovery of nuclear reactions brought about by slow neutrons"



Enrico Fermi

Italy

Rome University
Rome, Italy

b. 1901
d. 1954

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2006

Preface

This Lecture Note on Statistical Physics is aimed at undergraduate students in Physics at Department of Physics Padjadjaran University. Originally this text was collected from the first year (year of 2001) of my teaching on statistical physics and finally on the second year in 2002 typed by the help of my assistants. This text consisting six chapters which systematically discussing the introduction of thermodynamic, probability theory, kinetic theory, the principle of statistical mechanics, .Maxwell-Boltzman laws, Quantum Statistics and application of statistical distribution. I try to make this text available friendly user with some discussion and fundamental concept questions on each chapter. On this material I only discuss the kinetic theory of gas.

March 2006

Lecturer

I Made Joni

**CLASS SESION FROM 5th – 8th
23-9-2006 to 3-10-2006**

Objective

After the end of this chapter on kinetic theory of gas, student will be able to explain the kinetic theory of gas which is applied to the ideal gas system and real gas system correctly.

TIK(Pokok Bahasan):

Setelah mengikuti perkuliahan dengan pokok bahasan Teori Kinetik Gas ini, Mahasiswa akan dapat menguraikan Teori Kinetik Gas yang diaplikasikan pada sistem gas ideal dan gas sejati dengan benar (C3)

Topic: Kinetic Theory of Gas

Pokok Bahasa: Teori Kinetik Gas

Course Discription

On this chapter you will learn the basic concept to understand the pressure of gas from point of view of kinetic theory particles of the thermodynamic system. The most important to learn is the existence of kinetic of particles to hit the wall of container collectively which give the pressure on the wall. Starting from the physics of system then formulate the relation between the number of particles hitting the walls in flux of pressure which is occur in the system. If the space or volume of the system is made smaller, then particles will get compressed and each type of particles has their characteristics to receive pressure. This is called compressibility of gas. In order to make it simple, in the first place, you will neglect the potential interaction of particles. This kind of gas system is called ideal gas and its equation of state is called equation state of ideal gas. Furthermore you will learn the mechanics of interaction between particles which interact to each other in term equitation of state of real gas system and their characteristics.

Deskripsi Singkat:

Pada sub pokok bahasan ini Anda akan mempelajari konsep dasar untuk memahami arti suatu tekanan gas dari pandangan kinetik partikel-partikel yang ada pada suatu sistem termodinamika. Pengertian penting yang perlu dikaji adalah adanya gerakan kinetik partikel dalam menumbuk dinding secara kolektif akan mengakibatkan tekanan pada dinding. Berawal dari kejadian fisis ini kemudian derumuskan suatu hubungan antara jumlah partikel yang menumbuk dinding dalam fluks (mempertimbangkan luas permukaan) dengan tekanan yang terjadi pada sistem. Apabila ruang dalam partikel diperkecil, maka partikel akan mengalami kompresi dan setiap partikel mempunyai karakteristik terhadap kemampuan menerima tekanan. Hal ini yang sering disebut kompresibilitas suatu gas. Untuk mempermudah perumusan persamaan gas dan kajian awal tentang partikel gas dalam sistem, Anda tidak memperhatikan energi potensial partikel-partikelnya. Gas semacam ini disebut gas ideal dan persamaan keadaanya disebut persamaan gas ideal. Selanjutnya dengan memperhatikan mekanisme interaksi potensial partikel-partikelnya dirumuskan suatu persamaan gas sejati dan sifat-sifatnya.

1. Introduction

It is possible to compute the individual terms that make up the internal energy of the system composed of small numbers of particles such as our planetary system and an atom with a few electrons. However, when the number of particles is very large, as in many-electron atoms or in a gas composed of billions of molecules, calculations become mathematically unmanageable. Certain statistical method must then be used for computing average values of the dynamical quantities instead of accurate individual values for each member of the system. In addition, in these complex systems we are interested *not in the behavior of each individual component*, behavior which is generally not observable, but in *the behavior of the system as a whole*. The technique for dealing with these systems is called *statistical mechanics*. In this chapter we shall examine an adaptation methods of system composed of small particles to many particles. Can you see or feel that the individual atoms or molecules at work ? Rather we observe the result of large number of them acting in more or less organized manner.

Interrelation between the macroscopic (classical) and the microscopic (Statistical)

The conservation of energy and momentum are applicable to the motion of interacting particles. Now, we shall extend those principles of mechanics to system of many particles. The fact that we need a statistical approach when we are dealing with the macroscopic properties of matter is easily recognized when we note that in one cubic centimeter of a gas at STP, there are about 3×10^{19} molecules. It is not only practically impossible, but also unnecessary to take into account the motions of each of these molecules in detail to determine the bulk properties of the gas, such as its pressure or temperature. On the other hand, to make a statistical analysis of a many-particle system, we have to make some reasonable estimate about the dynamical state of each particle base on the general properties of the particles. We make this estimate by introducing the concept of the ***probability of distribution*** of the particles among the different dynamical states in which they may be found. When we introduce the idea of probability, this does not imply that we assume that the particles move randomly or in a chaotic way, without obeying any well-defined laws.

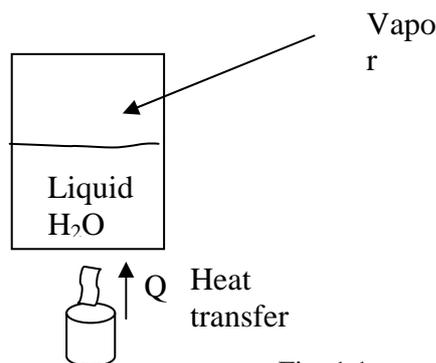


Fig. 1.1

Take a look at the Fig 1.1 above, the question arises from the microscopic point of view is how the energy stored in the system (H_2O). During the process T is increased and eventually all of liquid will become vapor. In the macroscopic point of view, we concerned with energy transferred as heat.

It is important to introduce the kinetic theory in this chapter for a better understanding to the properties of system of particles microscopically and then later relate them to the macroscopic point of view through statistical mechanic.

2. The Kinetic Theory of Gases

2.1. *Properties of matter*

Matter is made out of a great many atoms, or elementary parts, which interact electrically and obey the laws of mechanics, we try to understand why various aggregates of atoms behave the way they do.

It is obvious that this is a difficult subject, and we emphasize at the beginning that is in fact an *extremely* difficult subjects, and that we have to deal with it differently than we have dealt with the other subjects so far. In the case of mechanics and in the case of light, we were able to begin with a precise statement of some laws, like Newton's laws, or the formula for the field produced by an accelerating charge, from which a whole host of phenomena could be essentially understood, and which would produce a basis for our understanding of mechanics and of light from that time on. That is, we may learn more later, but we do not learn different physics, we only learn better methods of mathematical analysis to deal with the situation.

We cannot use this approach effectively in studying the properties of matter. We can discuss matter only in a most elementary way; it is much too complicated a subject to analyze directly from its specific basic laws, which are none other than the laws of mechanics and electricity. But these are a bit too far away from the properties we wish to study; it takes too many steps are, in themselves, fairly complicated. We will now start to take some of these steps, but while many of our analyses will be quite accurate, they will eventually get less and less accurate. We will have only a rough understanding of the properties of matter.

One of the reasons that we have to perform the analysis so imperfectly is that the mathematics of it requires a deep understanding of the theory of probability; we are not going to want to know where every atom is actually moving, but rather, how many move here and there on the average, and what the odds are for different effects. So this subject involves knowledge of the theory of probability, and our mathematics is not yet ready and we do not want to strain it too hard.

Secondly, and more important from a physical standpoint, the actual behaviour of the atoms is not according to classical mechanics, but according to quantum mechanics, and a correct understanding of the subject cannot be attained until we understand quantum mechanics. Here, unlike the case of billiard balls and automobiles, the difference between the classical mechanical laws and the quantum mechanical laws is very important and very significant, so that things that we will deduce by classical physics will be fundamentally incorrect. Therefore there will be certain things to be partially unlearned; however, we shall indicate in every case when a result is incorrect, so that we will know just where the "edges" are. One of the reasons for discussing quantum mechanics in the preceding chapters was to give an idea as to why. More or less, classical mechanics is incorrect in the various directions.

Why do we deal with the subject now at all? Why not wait a half a year, or a years, until we know the mathematics of probability better, and we learn a little quantum mechanics, and then we can do it in a more fundamental way? The answer is that it is a difficult subject, and the best way to learn is to do it slowly!. The first thing to do is to get some idea, more or less, of what ought to happen in different circumstances, and then, later, when we know the laws better, we will formulate them better.

Anyone who wants to analyze the properties of matter in a real problem might want to start by writing down the fundamental equations and then try to solve them mathematically. Although there are people who try to use such an approach, this people are the failures in this field; the real successes come to those who start from a *physical* point of view, people who have a rough idea where they are going and then begin by making the right kind of approximations, knowing what is big and what is small in a given complicated situation. These problems are so complicated that even an elementary understanding, although inaccurate and incomplete, is worth while having, and so the subject will be one that we shall go over again and again, each time with more and more accuracy, as we go through our course in physics.

Another reason for beginning the subject right now is that we have already used many of these ideas in, for example, chemistry, and we have even heard of some of them in high school. It is interesting to know the physical basic for these things.

As an interesting example, we all know that equal volumes of gases, at the same pressure and temperature, contain the same number of molecules. The law of multiple proportions, that when two gases combine in a chemical reaction the volumes needed always stand in simple integral proportions, was understood ultimately by Avogadro to mean that equal volumes have equal number of atoms. Now *why* do they have equal numbers of atoms? Can we deduce from Newton's laws that the number of atoms should be equal? We shall address ourselves to that specific matter in this chapter. In succeeding chapters, we shall discuss various other phenomena involving pressure, volumes, temperature, and heat.

We shall also find that the subject can be attacked from a monatomic point of view, and that there are many interrelationships of the properties of substances. For instance, when we compress something, it heats; if we heat it, it expands. There is a relationship between these two facts which can be deduced independently of the machinery underneath. This subject is called *thermodynamics*. The deepest understanding of thermodynamics, and that is what we shall do; we shall take the atomic viewpoint from the beginning and use it to understand the various properties of matter and the laws of thermodynamics.

Let us, then, discuss the properties of gasses from the standpoint of Newton's laws of mechanics.

The pressure of a gas

First, we know that a gas exerts a pressure, and we must clearly understand what this is due to. If our ears were a few times more sensitive, we should hear a perpetual rushing noise. Evolution has not developed the ear to that point, because it would be useless if it were so much more sensitive—we should hear a perpetual racket. The reason is that the eardrum is in contact with the air, and air is a lot of molecules in perpetual motion and this bang against the eardrum. In banging against the eardrum they make an irregular tattoo-boom, boom, boom—which we do not hear because the atoms are so small, and the sensitivity of the ear is not quite enough to notice it. The result of this perpetual bombardment is to push the drum away, but of course there is an equal perpetual bombardment of atoms on the other side of the eardrum, so the net force on it is zero. If we were to take the air away from one side, or change the relative amounts of air on the two sides, the eardrum would then be pushed one way or the other, because the amount of bombardment on one side would be greater than on the other. We sometimes feel this uncomfortable effect when we go up too fast in an elevator or an airplane, especially if we also have a bad cold (when we have a cold, inflammation closes the tube which connects the air on the inside of the eardrum with the outside air through the throat, so that the two pressures cannot readily equalize).

In considering how to analyze the situation quantitatively, we imagine that we have a volume of gas in a box, at one end of which is a piston which can be moved (Fig. 1.1). We would like to find out what force on the piston result from the fact that there are atoms in this box. The volume of the box is V , and as the atoms move around inside the box with various velocities they bang against the piston. Suppose there is nothing, a vacuum, on the outside of the piston. What of it? If the piston were left alone, and nobody held onto it, each time it got banged it would pick up a little momentum and it would gradually get pushed out of the box. So in order to keep it from being pushed out of the box, we have to hold it with a force F . The problem is, how much force? One way of expressing the force is to talk about the force per unit area: if A is the area of the piston, then the force on the piston will be written as a number times the area. We define the pressure, then, as equal to the force that we have to apply on a piston, divided by the area of the piston.

$$P = F / A \quad (1.1)$$

To take make sure we understand the idea (we have to derive it for another purpose anyway), the differential work dW done on the gas in compressing it by moving the piston in a differential amount $-dx$ would be the force times the change in the volume:

$$dW = F(-dx) = -PAdx = -PdV \quad (1.2)$$

(The area A times the distance dx is the volume change). The minus sign is there because, as we compress it, we *decrease* the volume; if we think about it we can see that if a gas is compressed, work is done on it.

How much force do we have to apply to balance the banging of the molecules? The piston receives from each collision a certain amount of momentum. A certain amount of momentum per second

will pour into the piston, and it will start to move. To keep it from moving, we must pour back into it the same amount of momentum per second from our force. Of course, the force is the amount of momentum per second that we must pour in. There is another way to put it : if we let go of the piston it will pick up speed because of the bombardments ; with each collision we get a little more speed, and the speed thus accelerates. The rate at which the piston picks up speed, or accelerates, is proportional to the force on it. So we see that the force, which we already have said is the pressure times the area, is equal to the momentum per second delivered to the piston by the colliding molecules.

To calculate the momentum per second is easy – we can do it in two parts: first, we find the momentum delivered to the piston by one particular atom in a collision with the piston, then we have to multiply by the number of collision per second that the atoms have with the wall. The force will be the product of these two factors. Now let us see what the two factors are: in the first place, we shall suppose that the piston is a perfect “reflector” for the atoms. If it is not, the whole theory is wrong and the piston will start to heat up and things will change, but eventually, when equilibrium has set in, the net result is that the collisions are effectively perfectly elastic. On the average, every particle that comes in leaves with the same energy. So we shall imagine that the gas is in a steady condition, and we lose no energy to the piston because the piston is standing still. In those circumstances, if a particle comes in with a certain speed, it comes out with the same speed and, we will say, with the same mass.

If \mathbf{v} is the velocity of an atom, and v_x is the x-component of \mathbf{v} , then mv_x is the x-component of momentum “in” ; but we also have an equal component of momentum “out” and so the total momentum delivered to the piston by the particle, in one collision, is $2mv_x$, because it is “reflected.”

Now, we need the number of collisions made by the atoms in a second, or in a certain amount of time dt ; then we divide by dt . How many atoms are hitting? Let us suppose that there are N atoms in the volume V , or $n = N/V$ in each unit volume. To find how many atoms hit the piston, we note that, given a certain amount of time t , if a particle has a certain velocity toward the piston it will hit during the time t , provided it is close enough. If it is too far away, it goes only part way toward the piston in the time t , but does not reach the piston. Therefore it is clear that only those molecules which are within a distance $v_x t$ from the piston are going to hit the piston in the time t . Thus the number of collisions in a time t is equal to the number of atoms which are in the region within a distance $v_x t$, and since the area of the piston is A , the volume occupied by the atoms which are going to hit the piston is $v_x t A$. But the number of atoms that are going to hit the piston is the volume times the number of atoms per unit volume, $nv_x t A$. Of course we do not want the number that hit in a time t , we want the number that hit per second, so we divide by the time t , to get $nv_x A$. (This time t could be made very short; if we feel we want to be more elegant, we call it dt , then differentiate, but it is the same thing).

So we find that the force is

$$F = nv_x A.2mv_x \quad (1.3)$$

see, the force *is* proportional to the area, if we keep the particle density fixed as we change the area! The pressure is then

$$P = 2nmv_x^2 \quad (1.4)$$

Now we notice a little trouble with this analysis: First, all the molecules do not have the same velocity, and they do not move in the same direction. So, all the v_x^2 's are different! So what we must do, of course, is to take an average of the v_x^2 's, since each one makes its own contribution. What we want is the square of v_x , averaged over all the molecules:

$$P = nm\langle v_x^2 \rangle \quad (1.5)$$

Did we forget to include the factor 2? No ; of all the atoms, only half we headed toward the piston. The other way, and if we take $\langle v_x^2 \rangle$, we are averaging the *negative* v_x^2 's squared, as well as the positive v_x^2 's. So when we just take $\langle v_x^2 \rangle$, without looking, we are getting twice as much as we want. The average of v_x^2 , for positive v_x , is equal to the average of v_x^2 for all v_x , times one half.

Now as the atoms bounce around, it is clear that there is nothing special about the “x-direction” ; the atoms may also be moving up and down, back and forth, in and out. Therefore it is going to be true that $\langle v_x^2 \rangle$, the average motion of the atoms in one direction, and the average in the other two directions, are all going to be equal :

$$\langle v_x^2 \rangle = \langle v_y^2 \rangle = \langle v_z^2 \rangle \quad (1.6)$$

It is only a matter of rather tricky mathematics to notice, therefore, that they are each equal to one-third of their sum, which is of course the square of the magnitude of the velocity :

$$\langle v_x^2 \rangle = \frac{1}{3} \langle v_x^2 + v_y^2 + v_z^2 \rangle = \frac{\langle v^2 \rangle}{3} \quad (1.7)$$

This has the advantage that we do not have to worry about any particular direction, and so we write our pressure formula again in this form :

$$P = \left(\frac{2}{3} \right) n \left(\frac{mv^2}{2} \right) \quad (1.8)$$

The reason we wrote the last factor as $(mv^2/2)$ is that this is the kinetic energy of the center-of-mass motion of the molecule. We find, therefore, that

$$PV = N \left(\frac{2}{3} \right) \left(\frac{mv^2}{2} \right) \quad (1.9)$$

With this equation we can calculate how much the pressure is, if we know the speeds.

As a very simple example let us take helium gas, or any other gas, like mercury vapor, or potassium vapor of high enough temperature, or argon, in which all the molecules are single atoms, for which we may suppose that there is no internal motion in the atom. If we had a complex molecule, there might be some internal motion, mutual vibrations, or something. We suppose that we may disregard that; this is actually a serious matter that we will have to come back to, but it turns out to be all right, and therefore, for this suppose, that the kinetic energy of the center-of-mass motion is all the energy there is. So for a monatomic gas, the kinetic energy is the total energy. In general, we are going to call U the total energy (it is sometimes called the total *internal* energy—may wonder why, since there is no *external* energy to a gas), i.e., all the energy of all the molecules in the gas, or the object, whatever it is.

For a monatomic gas we will suppose that the total energy U is equal to a number of atoms times the average kinetic energy of each, because we are disregarding any possibility of excitation or motion inside the atoms themselves. Then, in these circumstances, we would have

$$PV = \frac{2}{3} U \quad (1.10)$$

Incidentally, we can stop here and find the answer to the following question: Suppose that we take a can of gas and compress the gas slowly, how much pressure do we need to squeeze the volume down? It is easy to find out, since the pressure is $2/3$ the energy divide by V . As we squeeze it down, we do work on the gas and we thereby increase the energy U . So we are going to have some kind of a differential equation : If we start out in a given circumstance with a certain energy and a certain volume, we then know the pressure. Now we start the squeeze, but the moment we do, the energy U increases and the volume V decreases, so the pressure goes up.

So, we have to solve a differential equation, and we will solve it in a moment. We must first emphasize, however, that as we are compressing this gas, we are supposing that all the work goes into increasing the energy of the atoms inside. We may ask, “Isn’t that necessary? Where else could it go ?” It turns out that it can go another place. There are what we call “heat leaks” through the walls: the hot (i.e., fast-moving) atoms that bombard the walls, heat the walls, and energy goes away. We shall suppose for the present that this is not the case.

For somewhat wider generality, although we are still making some very special assumptions about our gas, we shall write, not $PV = 2/3 U$, but

$$PV = (\gamma - 1) U \quad (1.11)$$

It is written $(\gamma - 1)$ times U for conventional reasons, because we will deal with a few other cases later where the number in front of U will not be $2/3$, but will be a different number. So, in order to do the thing in general, we call it $\gamma - 1$, because people have been calling it that for almost one hundred years. This γ , then, is $5/3$, because $5/3 - 1$ is $2/3$ for a monatomic gas like helium.

We have already noticed that when we compress a gas the work done is $-PdV$. A compression in which there is no heat energy added or removed is called an adiabatic compression, from the Greek a (not) + *dia*(through) + *bainein*(to go). (The word adiabatic is used in physics in several ways, and it sometimes hard to see what is common about them). That is, for an adiabatic compression all the work done goes into changing the internal energy. That is the key-that there are no other losses of energy-for then we have $P dV = -dU$. But since $U = PV/(\gamma - 1)$, we may write

$$dU = (PdV + VdP)/(\gamma - 1) \quad (1.12)$$

So we have $P dV = -(P dV + V dP)/(\gamma - 1)$, or, rearranging the terms, $\gamma P dV = -V dP$, or

$$(\gamma dV/V) + (dP/P) = 0 \quad (1.13)$$

Fortunately, assuming that γ is constant, as it is for a monatomic gas, we can integrate this : it gives $\gamma \ln V + \ln P = \ln C$, where $\ln C$ is the constant of integration. If we take the exponential of both sides, we get the law $PV^\gamma = C$ (a constant) (1.14)

In other words, under adiabatic conditions, where the temperature rises as we compress because no heat is being lost, the pressure times the volume to the $5/3$ power is a constant for a monatomic gas! Although we derived it theoretically, this is, in fact, the way monatomic gases behave experimentally.

Compressibility of radiation

We may give one other example of the kinetic theory of a gas, one which is not used in chemistry so much, but is used in astronomy. We have a large number of photons in a box in which the temperature is very high. (The box is, of course the gas in a very hot star. The sun is not enough; there are still too many atoms, but at still higher temperatures in certain very hot stars, we may neglect the atoms and suppose that the only objects that we have in the box are photons.). Now then, a photon has a certain momentum \mathbf{p} . (We always find that we are in terrible trouble when we do kinetic theory; p is the pressure, but p is the momentum; v is the volume, but v is the velocity; T is the temperature, but T is the kinetic energy or the time or the torque; one must keep one's wits about one!) This \mathbf{p} is momentum, it is a vector. Going through the same analysis as before, it is the x-component of the vector \mathbf{p} which generates the 'kick,' and twice the x-component of the vector \mathbf{p} is the momentum which is given in the kick. Thus $2p_x$ replaces $2mv_x$, and in evaluating the number of collisions, v_x is still v_x , so when we get all the way through, we find that pressure in Eq.(1.4) is, instead,

$$P = 2 n p_x v_x \quad (1.15)$$

Then, in the averaging, it becomes n times the average of $p_x v_x$ (the same factor of 2) and, finally, putting in the other two directions, we find

$$P V = \frac{N \langle \mathbf{p} \cdot \mathbf{v} \rangle}{3} \quad (1.16)$$

This checks with the formula (1.9), because the momentum is $m\mathbf{v}$; it is a little more general, that is all. The pressure times the volume is the total number of atoms times $1/3(\mathbf{p} \cdot \mathbf{v})$, averaged.

Now, for photons, what is $\mathbf{p}\cdot\mathbf{v}$? The momentum and the velocity are in the same direction, and the velocity is the speed of light, so this is the momentum of each of the objects, times the speed of light. The momentum times the speed of light of every photon is its energy ; $E = pc$, so these terms are the energies of each of the photon, and we should, of course, take an average energy, times the number of photons. So we have $1/3$ of the energy inside the gas :

$$PV = U/3 \text{ (photon gas)} \quad (1.17)$$

For photons, then, since we have $1/3$ in front, $(\gamma - 1)$ in (39.11) is $1/3$, or $\gamma = \frac{4}{3}$, and we have discovered that radiation in a box obeys the law

$$PV^{4/3} = C \quad (1.18)$$

So we know the compressibility of radiation! That is what is used in an analysis of the contribution of radiation pressure in a star, that is how we calculate it, and how it changes when we compress it. What wonderful things are already within our power!

2.2. Temperature and kinetic energy

So far we have not dealt with temperature; we have purposely been avoiding the temperature. As we compress a gas, we know that the energy of the molecules increases, and we are used to saying that the gas gets hotter; we would like to understand what this has to do with the temperatures. If we try to do the experiment, not adiabatically but at what we call *constant temperature*, what are we doing ? We know that if we take two boxes of gas and let them sit next to each long enough, even if at the start they were at what we call different temperatures, they will in the end come to the same temperature. Now what does that mean ? That means that they get to a condition that they would get to if we left them alone long enough! What we mean by equal temperature is just that-the final condition when things have been sitting around interacting with each other long enough.

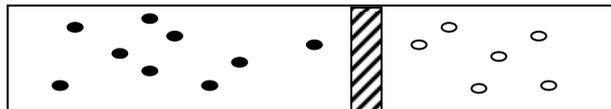


Fig. 1.2 Atoms of two different monatomic gases are separated by a movable piston.

Let us consider, now, what happens if we have two gases in containers separated by movable piston as in Fig. 1.2 (just for simplicity we shall take two monatomic gases, say helium and neon). In container (1) the atoms have mass m_1 , velocity v_1 , and there are n_1 per unit volume, and in the other container the atoms have mass m_2 , velocity v_2 , there are n_2 atoms per unit volume. What are the condition for equilibrium?

Obviously, the bombardment from the left side much be such that it moves the piston to the right and compresses the other gas until its pressure builds up, and the thing will thus slosh back and forth, and will gradually come to rest at a place where the pressure are equal on both sides. So we can arrange that the pressures are equal ; that just means that the internal energies per unit volume are equal, or that the number n times the average kinetic energies on each side are equal. What we have to try to prove, eventually. Is that the *numbers themselves* are equal. So far, all we know is that the numbers times the kinetic energies are equal,

$$n_1(m_1 v_1^2/2) = n_2(m_2 v_2^2/2)$$

From (1.8), because the pressure are equal. We must realize that this is not the only condition over the long run, but something else must happen more slowly as true complete equilibrium corresponding to equal temperatures sets in.

To see the idea, suppose that the pressure on the left side were developed by having a very high density but a low velocity. By having a large n and a small v , we can get the same pressure as by having a small n and a large v . The atoms may be moving slowly but the packed nearly solidly, or there may be fewer but they are hitting harder. Will it say like that forever? At the first we might think so, but then we think again and find we have forgotten one important point. That is, that the intermediate piston does not receive a steady pressure ; it wiggles, just like the eardrum that we were first talking about, because the banging are not absolutely uniform. There is not a perpetual, steady pressure, but a tattoo-the pressure varies, and so the thing jiggles. Suppose that the atoms on the right side are not jiggling much, but those on the left are few and far between and very energetic. The piston will, now and then, get a big impulse from the left, and will be driven against the slow atoms on the right, giving them more speed. (As each atom collides with the piston, it either gains or loses energy, depending upon whether the piston is moving one way or the other when the atom strikes it) So, as a result of the collisions, the piston finds it self jiggling. Jiggling, jiggling, and this shakes the other gas-it gives energy to the other atoms, and they build up faster motions, until they balance the jiggling that the piston is giving to them. The system comes to some equilibrium where the piston is moving at such a mean square speed that it picks up energy from the atoms at about the same rate as it puts energy back into them. So the piston picks up a certain mean irregularity in speed, and it is our problem to find it. When we do find it, we can solve our problem better, because the gases will adjust their velocities until the rate at which they are trying to pour energy into each other through the piston will become equal.

It is quite difficult to figure out the details of the piston in this particular circumstance; although it is ideally simple to understand, it turns out to be a little harder to analyze. Before we analyze that, let us analyze another problem in which we have a box of gas but now we have two different kinds of molecules in it, having masses m_1 and m_2 , velocities v_1 and v_2 , and so forth ; there is now a much more intimate relationship. If all of the No. 2 molecules are standing still, that condition is not going to last, because they get kick by the No. 1 molecules, then maybe that will not last either-they will past the energy back to the No. 1 molecules. So when both gases are in the same box, the problem is to find the rule that determines the relative speeds of the two.

This is still a very difficult problem, but we will solve it as follows. First we consider the following sub-problem (again this is one of those cases where-never mind the derivation-in the end the result is very simple to remember, but the derivation is just ingenious). Let us suppose that we have two molecules, of different mass, colliding, and that the collision is viewed on the center-of mass (CM) system. In order to remove a complication, we look at the collision in the CM. As we know from the laws of collision, by the conservation of momentum and energy, after the molecules collide the only way they can move is such that each maintains its own original speed-and they just change they direction. So we have an average collision that looks like that in Fig. 39-3. Suppose we imagine that they are all initially moving horizontally. Of course, after the first collision some of them are moving at an angle. In other words, if they were all going horizontally, then at least some would later be moving vertically. Now in some other collision, they would be coming in from another direction, and then they would be twisted at still another angle. So even if they were completely organized in the beginning, they would get sprayed around at all angles, and then the sprayed ones would get sprayed some more, and sprayed some more, and sprayed some more. Ultimately, what will be the distribution? Answer : *it will be equally likely to find any pair moving in any direction in space.* After that further collisions could not change the distribution.

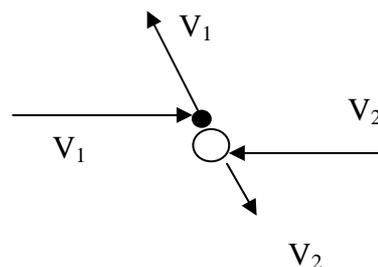


Fig. 1.3 A collision between unequal molecules, viewed in the CM system.

They are equally to go in all directions, but how do we say that? There is of course *no* likelihood that they will go in any specific direction, because a specific direction is too exact, so we have to talk about per unit ‘something.’ The idea is that any area on a sphere centered at a collision point will have just as many molecules going through it as go through any other equal area on a sphere. So the result of the collisions will be distributing the directions so that equal areas on a sphere will have equal probabilities.

Incidentally, if we just want to discuss the original direction and some other direction an angle θ from it, it is an interesting property that the differential area of a sphere of unit radius is $\sin \theta d\theta$ times 2π , and that is the same as the differential of $\cos \theta$. So what it means is that the cosine of the angle θ between any two directions is equally likely to be anything from -1 to $+1$.

Next, we have to worry about the actual case, where we do not have the collision in the CM system, but we have two atoms that are coming together with vector velocities \mathbf{v}_1 and \mathbf{v}_2 . What happens now? We can analyze this collision with the vector velocities \mathbf{v}_1 and \mathbf{v}_2 in the following way: we first say that there is a certain CM; the velocity of the CM is given by the “average” velocity, with weights proportional to the masses, so the velocity of the CM is $\mathbf{v}_{CM} = (m_1\mathbf{v}_1 + m_2\mathbf{v}_2)/(m_1+m_2)$. If we watch this collision in the CM system, then we see a collision just like that in Fig. 1.3, with a certain relative velocity \mathbf{w} coming in. The relative velocity is just $\mathbf{v}_1 - \mathbf{v}_2$. Now the idea is that, first, the whole CM is moving, and in the CM there is a relative velocity \mathbf{w} , and the molecules collide and come off in some new direction. All this happens while the CM keeps right on moving, without any change.

Now then, what is the distribution resulting from this? From our previous argument we conclude this: that at equilibrium, all directions for \mathbf{w} are equally likely, relative to the direction of the motion of the CM.* There will be no particular correlation, in the end, between the direction of the motion of the relative velocity and that of the motion of the CM. Of course, if there were, the collisions would spray it about, so it is all sprayed around. So the cosine of the angle between \mathbf{w} and \mathbf{v}_{cm} is zero on the average. That is,

$$(\mathbf{W} \cdot \mathbf{V}_{CM}) = 0 \quad (1.19)$$

But $\mathbf{w} \cdot \mathbf{v}_{cm}$ can be expressed in terms of v_1 and v_2 as well:

$$\begin{aligned} W \cdot V_{CM} &= \frac{(v_1 - v_2)(m_1 v_1 + m_2 v_2)}{m_1 + m_2} \\ W \cdot V_{CM} &= \frac{(m_1 v_1^2 - m_2 v_2^2) + (m_2 - m_1)(v_1 \cdot v_2)}{m_1 + m_2} \end{aligned} \quad (1.20)$$

First, let us look at the $v_1 \cdot v_2$; what is the average of $v_1 \cdot v_2$? That is, what is the average of the component of velocity of one molecule in the direction of another? Surely there is just as much likelihood of finding any given molecule moving one way as another. The average of the velocity v_2 in any direction is zero. Certainly, then, in the direction of v_1 , v_2 has zero average. So, the average of $v_1 \cdot v_2$ is zero! Therefore, we conclude that the average of $m_1 \cdot v_{12}$ must be equal to the average of $m_2 \cdot v_{22}$. That is, the average kinetic energy of the two must be equal:

$$\frac{1}{2} m_1 v_1^2 = \frac{1}{2} m_2 v_2^2 \quad (1.21)$$

If we have two kinds of atoms in a gas, it can be shown, and we presume to have shown it, that the average of the kinetic energy of the other, when they are both in the same gas in the same box in equilibrium. That means that the heavy ones will move slower than the light ones; this is easily shown by experimentation with “atoms” of the different masses in an air trough.

Now we should like to go one step further, and say that if we have two different gases separated in a box, they will also have equal average kinetic energy when they have finally come to equilibrium, even though they are not in the same box. We can make the argument in a number of ways. One way is to argue that if we have a fixed partition with a tiny hole in it (Fig. 1.4) so that one gas could leak one

through the holes while the other could not, because the molecules are too big, and these has attained equilibrium, then we know that in one part, where they are mixed, they have the same average kinetic energy, but come some through the hole without loss of kinetic energy, so the average kinetic energy in the pure gas and in the mixture must be the same. That is not too satisfactory, because maybe there are no holes, for the kind of molecule, the separate one kind from the other.

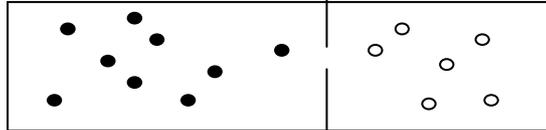


Fig. 1.4 Two gases in a box with a semi permeable membrane

Let us now go back to the piston problem. We can give an argument which shows that the kinetic energy of this piston must also be $\frac{1}{2} (m_2 \cdot v_{22})$. Actually, that would be the kinetic energy due to the purely horizontal motion of the piston, so, forgetting its up and down motion, it will have to be the same as $\frac{1}{2} (m_2 \cdot v_{22})$, likewise, from the equilibrium on the other side, we can prove that the kinetic energy of the piston is $\frac{1}{2} (m_1 \cdot V_{12})$. Although this is not on the middle of the gas, but is on one side of the gas, we can still make the argument, although it is a little more difficult, that the average kinetic energy of the piston and of the gas molecules are equal as a result of all the collisions.

If this still does not satisfy us, we may make an artificial example by which the equilibrium is generated by an object which can be hit on all sides. Suppose that we have a short rod with a ball on each end sticking through the piston, on a frictionless sliding universal joint. Each ball is round, like one of the molecules, and can be hit on all sides. This whole object has a certain total mass, m . Now, we have the gas molecules with mass m_1 and mass m_2 as before. The result of the collisions, by the analysis that was made before, is that the kinetic energy of m because of collisions with molecules on the other side, it has to be $\frac{1}{2} m_2 v_2^2$ on the average. So, therefore, both sides have to have the same kinetic energy when they are in the thermal equilibrium. So, although we only proved it for a mixture of gases at the same temperature.

Thus when we have two gases at the same temperature, the mean kinetic energy of the CM motions are equal.

The mean molecular kinetic energy is a property only of the “ temperature. “ Being a property of the “ temperature, “ *and not of the gas* , we can use it as a *definition* of the temperature. The mean kinetic energy of a molecule is thus some function of the temperature. But who is to tell us what scale to use for the temperature? We may arbitrarily *define* the scale of temperature so that the mean energy is linearly proportional to the temperature. The best way to do it would be to call the mean energy itself “ the temperature. “ That would be the simplest possible function. Unfortunately, the scale of temperature has been chosen differently, between the energy of a molecule and a degree of absolute temperature called a degree Kelvin. The constant of proportionality is $k = 1.38 \times 10^{-23}$ joule for every degree Kelvin.* So if T is absolute temperature, our definition says that the mean molecular kinetic energy is $\frac{3}{2} kT$. (The $\frac{3}{2}$ is put in as the matter of convenience, so as to get rid of it somewhere else.)

We point out that the kinetic energy associated with the component of motion in any particular direction is only $\frac{1}{2} kT$. The three independent directions that are involved make it $\frac{3}{2} kT$.

2.3. The ideal gas law

Now, of course, we can put our definition of temperature into Eq. (1.9) and so find the law for the pressure of gases as a function of the temperature : it is that the pressure times the volume is equal to the total number of atoms times the universal constant k , times the temperature :

$$PV = NKT \quad (1.22)$$

Furthermore, at the same temperature and pressure and volume, the number of atoms is determined; it too is a universal constant! So equal volumes of different gases, at the same pressure and temperature, have the same number of molecules, because the Newton’s laws. That is an amazing conclusion!

In practice, when dealing with molecules, because the numbers are so large, the chemists have artificially chosen a specific number, a very large number, and called it something else. They have a number that they call a mole. A mole is merely a handy number. Why they did not choose 10^{24} objects, so it would come out even, is a historical question. They happened to choose, for convenient number of objects on which they standardize, $N_0 = 6.02 \times 10^{23}$ objects, and this is called a mole of objects. So instead of measuring the number of molecules in units, they measure in terms of numbers of moles. In terms of N_0 we can write the number of moles, times the number of atoms in a mole, times kT , and if we want to, we can take the number of atoms in a mole times k , which is a mole's worth of k , and call it something else, and we do—we call it R . A mole's worth of k is 8.317 joules : $R = N_0k = 8.317 \text{ j.mole}^{-1} \cdot \text{K}^{-1}$. Thus we also find the gas law written as the number of moles (also called N) times RT , or the number of atoms, times kT :

$$PV = NRT \quad (1.23)$$

It is the same thing, just a different scale for measuring numbers. We use 1 as a unit, and a chemists use 6×10^{23} as a unit!

We now make one more remark about our gas law, and that has to do with the law for objects other than monatomic molecules. We have dealt only with the CM motion of the atoms of monatomic gas. What happens if there are forces present? First, consider the case that the piston is held by a horizontal spring, and there are forces on it. The exchange of jiggling motion between atoms and piston at any moment does not depend on where the piston is at that moment, of course. The equilibrium conditions are the same. No matter where the piston is, its speed of motion must be such that it passes energy to the molecules in just the right way. So, it makes no difference about the spring. The speed at which the piston has to move, on the average, is the same. So our theorem, that the mean value of the kinetic energy in one direction is $\frac{1}{2} kT$, is true whether there are forces present or not.

Consider, for example, a diatomic molecule composed of atoms m_A and m_B what we have proved is that the motion of the CM of part A and B are such that $\langle \frac{1}{2} m_A v_A^2 \rangle = \langle \frac{1}{2} m_B v_B^2 \rangle = \frac{3}{2} kT$. How can this be, if they are held together? Although they are held together, when they are spinning and turning in there, when something hits them, exchanging energy with them, the only thing that counts is how fast they are moving. That alone determines how fast they exchange energy of collisions. At the particular instant, the force is not an essential point. Therefore the same principle is right, even when there are forces.

Let us prove, finally, that the gas law is consistent also with a disregard of the internal motion. We did not really include the internal motion before; we just treated a monatomic gas. But we shall now show that an entire object, considered as a single body of total mass M , has a velocity of the CM such that

$$\frac{1}{2} M v_{CM}^2 = \frac{3}{2} kT \quad (1.24)$$

In other words, we can consider either the separate pieces or the whole thing! Let us see the reason for that : The mass of the diatomic molecules is $M = (m_A v_A + m_B v_B)/M$. Now we need $\langle v_{CM}^2 \rangle$. If we square v_{CM} , we get

$$v_{CM}^2 = \frac{m_A^2 v_A^2 + 2m_A m_B v_A \cdot v_B + m_B^2 v_B^2}{M^2}$$

Now we multiply $\frac{1}{2} M$ and take the average, and thus we get

$$\begin{aligned} \frac{1}{2} M v_{CM}^2 &= \frac{m_A \frac{3}{2} kT + 2m_A m_B \langle v_A \cdot v_B \rangle + m_B \frac{3}{2} kT}{M} \\ &= \frac{3}{2} kT + \frac{2m_A m_B \langle v_A \cdot v_B \rangle}{M} \end{aligned}$$

(We have used the fact that $(m_A v_a + m_B v_B)/M = 1$. Now what is $\langle v_a \cdot v_B \rangle$? (It had better be zero!) To find out, let us use our assumption that the relative velocity, $w = v_a - v_B$ is not any more likely to point in one direction than in another – that is, that its average component in any direction is zero. Thus we assume that

$$\langle w \cdot v_{CM} \rangle = 0$$

But what is $w \cdot v_{CM}$? It is

$$\begin{aligned} w \cdot v_{CM} &= \frac{(v_A - v_B)(m_A v_A + m_B v_B)}{M} \\ &= \frac{m_A v_A^2 + (m_B - m_A)(v_A \cdot v_B) - m_B v_B^2}{M} \end{aligned}$$

Therefore, since $\langle m_A v_A^2 \rangle = \langle m_B v_B^2 \rangle$, the first and last terms cancel out on the average, and we are left with

$$(m_B - m_A) \langle v_A \cdot v_B \rangle = 0$$

Thus if m_A is not equal with m_B , we find that $\langle v_A \cdot v_B \rangle = 0$, and therefore that the bodily motion of the entire molecule, regarded as a particle of mass M , has a kinetic energy, on the average, equal to $3/2 kT$.

Incidentally, we have also proved at the same time that the average kinetic energy of the internal motions of the diatomic molecule, disregarding the bodily motion of the CM, is $3/2 kT$! For, the total kinetic energy of the parts of the molecule is $1/2 m_A v_A^2 + 1/2 m_B v_B^2$, whose average is $3/2 kT + 3/2 kT$, or $3kT$. The kinetic energy of the center – of – mass motion is $3/2 kT$, so the average kinetic energy of the rotational and vibratory motions of the two atoms inside the molecule is the difference, $3/2 kT$.

The theorem concerning the average energy of the CM motion is general: for any object considered as a whole, with forces present or no, for every independent direction of motion that there is, the average kinetic energy in that motion is $3/2 kT$. These “independent direction of motion” are sometimes called *the degrees of freedom* of the system. The number of degrees of freedom of a molecule composed of r atoms is $3r$, since each atom needs three coordinates to define its position. The entire kinetic energy of the molecule can be expressed either as the sum of the kinetic energies of the separate atoms, or as the sum of the kinetic energy of the CM motion plus the kinetic energy of the internal motions. The latter can sometimes be expressed as a sum of rotational kinetic energy of the molecule and vibrational energy, but this is an approximation. Our theorem, applied to the r -atom molecule, says that the molecule will have, on the average, $3rkT/2$ joules of kinetic energy, of which $3/2 kT$ is kinetic energy of the center – of – mass motion of the entire molecule, and the rest, $3/2(r - 1)kT$, is internal vibrational and rotational kinetic energy.

2.4. Real Gas

The ideal gas equation, Eq. (1.22)

$$U = NE_{K_{ave}} = \frac{3}{2} NkT$$

describes the behavior of gas in which there no intermolecular forces and the molecular s are considered as mass point; therefore, the equation is a good approximation for real gases only insofar as the effect of intermolecular forces and of molecular sizes is negligible. Such condition exist only at high temperatures (or large molecular kinetic energy) or at low densities (or large intermolecular separations) or both.

A result known as the *virial theorem* allows us to write the equation of state for real gas when the intermolecular forces are taken into account as

$$PV = kNT + \frac{1}{3} \left(\sum_{\text{allpart}} F_{ij} r_{ij} \right)_{\text{AVE}} \quad (1.25)$$

where

F_{ij} = force between molecule i and j

r_{ij} = vector separation

N = Number of particle

Let us evaluate the last term of equation (1.25) by using virial theorem by R.J.E.Clausius (Germany scientist)

$$PV = kNT \left[1 + A(T) \left(\frac{N}{V} \right) + B(T) \left(\frac{N}{V} \right)^2 + \dots \right] \quad (1.26)$$

where A(T) and B(T) = *virial coefficients*, if the density is low (N/V low), the equation above shows an ideal gas, but if the density is high this equation lead to a real gas.

Consider a particle of mass moving under the action of the force F define the scalar A = mvr

$$\frac{dA}{dt} = m \frac{dv}{dt} r + mv \frac{dr}{dt} = mar + mv^2 = F \cdot r + 2E_k$$

If we take the time average of this equation,

$$\left(\frac{dA}{dt} \right)_{\text{ave}} = (F \cdot r)_{\text{ave}} + 2(E_k)_{\text{ave}} \quad (1.27)$$

Over an interval τ , the time average of any quantity f(t) that depends on the time is defined by

$$f(t)_{\text{ave}} = \frac{1}{\tau} \int_0^{\tau} f(t) dt$$

In our case, than,

$$\left(\frac{dA}{dt} \right)_{\text{ave}} = \frac{1}{\tau} \int_0^{\tau} \left(\frac{dA}{dt} \right) dt = \frac{1}{\tau} \int_0^{\tau} dA \quad (1.28)$$

If the time τ is very large and if A does not increase indefinitely with time, the quantity $(A-A_0)/\tau$ can be so small that it can be considered as zero

$$\left(\frac{dA}{dt} \right)_{\text{ave}} = \frac{A - A_0}{\tau} = \text{zero} \quad (1.29)$$

Therefore from equation (1.27) we have the average kinetic energy

$$(E_k)_{\text{ave}} = -\frac{1}{2} (F \cdot r)_{\text{ave}} \quad (1.30)$$

This is the virial theorem for a particle. The quantity $-1/2 (F \cdot r)_{\text{ave}}$ is called the virial of the particle. Now consider a system compose of two particle m_1 and m_2 . We define the scalar quantity

$$A = m_1 v_1 r_1 + m_1 v_1 \frac{dr_1}{dt} + m_2 \frac{dv_2}{dt} r_2 + m_2 r_2 \frac{dr_2}{dt} \quad (1.31)$$

Taking the time derivative of A, we have

$$\frac{dA}{dt} = (m_1 a_1 r_1 + m_2 a_2 r_2) + m_1 r_1^2 + m_2 r_2^2$$

The last term on the right is twice the kinetic energy, E_k , of the system. Then we may write

$$\frac{dA}{dt} = 2E_k + m_1 a_1 r_1 + m_2 a_2 r_2$$

Assume that external force on particle 1 is F_1 and the internal force on 1 is F_{12} ; on particle 2 the external and internal forces are F_2 and F_{21} , respectively.

Remembering that $F_{12} = -F_{21}$ and $r_{12} = r_1 - r_2$, we see that

$$\begin{aligned} m_1 a_1 \vec{r}_1 + m_2 a_2 \vec{r}_2 &= (\vec{F}_1 + \vec{F}_{12}) \vec{r}_1 + (\vec{F}_2 + \vec{F}_{21}) \vec{r}_2 \\ &= \vec{F}_1 \vec{r}_1 + \vec{F}_2 \vec{r}_2 + \vec{F}_{12} (\vec{r}_1 - \vec{r}_2) \end{aligned}$$

Therefore our equation become

$$\begin{aligned} \frac{dA}{dt} &= 2E_k + \vec{F}_1 \vec{r}_1 + \vec{F}_2 \vec{r}_2 + \vec{F}_{12} \cdot \vec{r}_{12} \\ &= 2E_k + B \end{aligned}$$

where, to simplify the writing, we have called the expression inside the parentheses B. Taking the time average of this equation, we have

$$\left(\frac{dA}{dt} \right)_{ave} = 2E_k + B_{ave} \quad (1.32)$$

so that

$$2Ek_{ave} = -B_{ave} = -(\vec{F}_1 \vec{r}_1 + \vec{F}_2 \vec{r}_2 + \vec{F}_3 \vec{r}_3)_{ave}$$

It is generalized for many particles

$$E_{ave} = -\frac{1}{2} \left(\sum_{\substack{\text{all} \\ \text{particles}}} \vec{F}_i \vec{r}_i + \sum_{\substack{\text{all pairs} \\ \text{of particles}}} \vec{F}_{ij} \vec{r}_{ij} \right)_{ave} \quad (1.33)$$

Now, assume a gas composed of molecules subject to their mutual interaction and also to the interaction with the walls of the container. We shall also assume for simplicity that the container is cube of side a as shown in Fig 1.5.

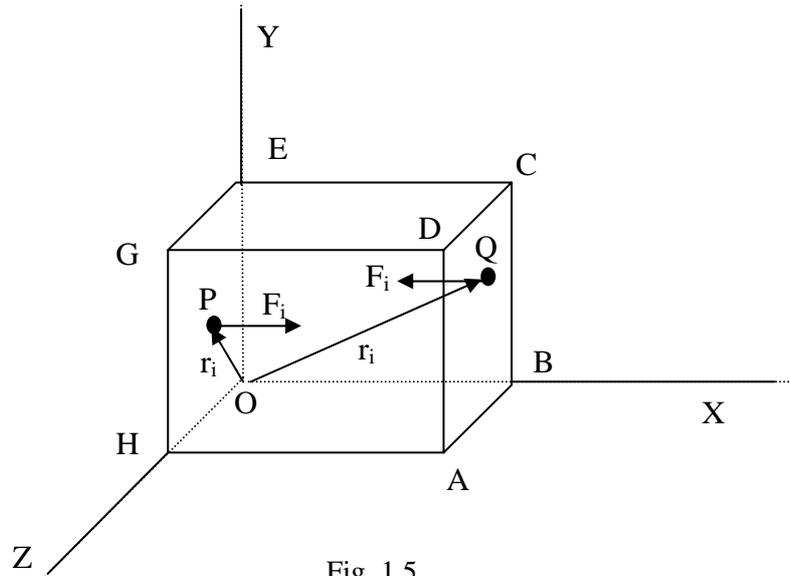


Fig. 1.5

To evaluate equation (1.33), we start with the first summation, corresponding to the external forces. A molecule experiences an external force only when the molecule hits the walls and bounces back. We may assume that the force is perpendicular to the wall, an assumption is only statistically correct. At the wall only wall OEGH, OBCE, and OHAB doesn't contribute to the virial because our choice at origin $X=0$.

At wall ABCD a particle hitting Q suffer a force parallel but opposite to OX and at point Q,

$$\vec{F}_i = -\hat{i}F_i, X_i = a. \text{ Therefore}$$

$$F_i r_i = -F_i a$$

A similar result is obtained for the walls CDGE and ADGH, so that the total contribution to the six walls is

$$\sum F_i a = a \sum F_i = -Fa = -Pa^3$$

where $V = a^3$

$$\sum_i F_i r_i = -3Pa^3 = -3PV$$

Equation (1.27) then becomes

$$E_{ave} = \frac{3}{2}PV - \frac{1}{2} \left(\sum_{ij} F_{ij} r_{ij} \right)_{ave}$$

or

$$PV = NkT + \frac{1}{3} \left(\sum_{ij} F_{ij} r_{ij} \right)_{ave} \quad (1.34)$$

This result provides a relation between the time averages of the kinetic and the potential energies of the particle and shows that quantities are coupled.

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Key Question

When you read the whole part of this chapter, you use the following question to guide your understanding:

1. What does it mean by pressure of gas related to the kinetic of particles within the system?
2. How do you relate the concept of temperature with the velocity of particles?
3. What does it mean by ideal and real gas?
4. What does it mean by the equation of state of a system?
5. How do the characteristics of the particles in the system in thermal equilibrium?
6. What does it mean by compressibility of a gas particles? Do this compressibility constant? If it is constant give detailed explanation?
7. What does it mean by degree of freedom of a system and the partition of energy?
8. Explain the definition of entropy of system based on the kinetic of ideal gas particles?

Formatives Test:

- 1) A nuclear power station is designed to generate 2000 MW of electrical power. To do this it maintains a reservoir of superheated steam at a temperature of 400 K. Waste heat from the reactor is transferred by a heat exchanger to circulating sea water at 300 K. What is the minimum possible rate of nuclear energy generation needed?
- 2) You are asked to design a refrigerated warehouse to maintain perishable food at a temperature of 5 C in an external environment of up to 30 C. The size of the warehouse and its degree of thermal insulation mean that the refrigeration plant must extract heat at a rate of 1000 KW. As a first step you must supply the local electricity company with an estimate for the likely electrical consumption of the proposed warehouse. What value would you suggest as a working minimum?
- 3) A hypothetical cycle consists of two isotherms ($T_1 > T_2$) and two isobars ($p_1 > p_2$) and is performed reversibly with n moles of an ideal gas as its working substance.
 - a) Sketch this cycle on a pV diagram – indicating the directions of change corresponding to its operation as a heat engine.
 - b) In principle, how many heat reservoirs are required to perform the cycle reversibly?
 - c) Show by a detailed consideration of the heat absorbed and work done that the efficiency of the cycle is identical to that of an ideal heat engine operating with two reservoirs at temperatures T_1 and T_2 .
- 4) One mole of ideal gas is maintained at a temperature T .
 - a) What is the minimum work needed to reduce its volume by a factor of e ($=2.718\dots$) ?
 - b) What is the entropy loss of the gas during this process?
- 5) 1 kg of water at 20C is placed in thermal contact with a heat reservoir at 80C. What is the entropy change of the total system (water plus reservoir) when equilibrium has been re-established?
- 6) Demonstrate that the entropy change for n moles of ideal gas can also be written as

$$\Delta S = c_p \ln \left(\frac{T_2}{T_1} \right) - nR \ln \left(\frac{p_2}{p_1} \right)$$

Where T_1, p_1 and T_2, p_2 are the initial and final pressures respectively and c_p is the specific heat capacity at constant pressure.

Numerical Answers of formatives Test

- 1) 8000 MW
- 2) 90 KW
- 3b) An infinite number.
- 4a) $R T$ Joules
- 4b) R Joules per Kelvin
- 5) +78 Joules per Kelvin
- 6) Hint. Use the ideal gas law and the known relation between c_p and c_v .