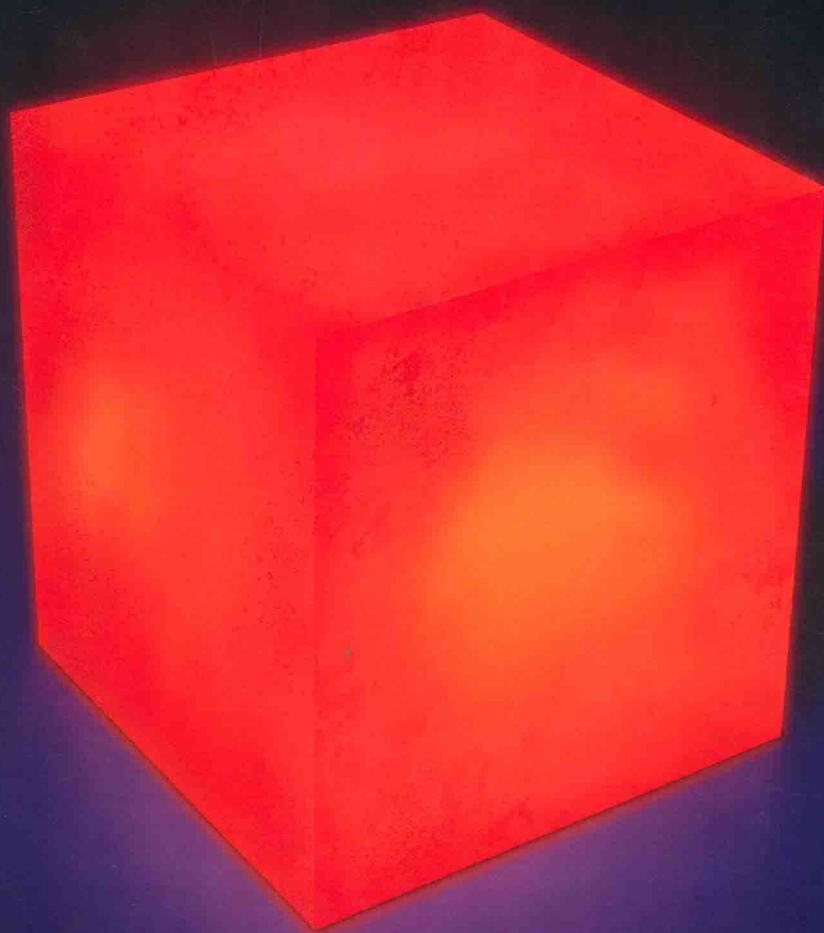


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# Atkins' PHYSICAL CHEMISTRY

10th Edition



Peter Atkins | Julio de Paula

# Atkins' PHYSICAL CHEMISTRY

Tenth edition

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Impression: 1

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# FUNDAMENTAL CONSTANTS

Constant	Symbol	Value		
			Power of 10	Units
Speed of light	$c$	2.997 924 58*	$10^8$	$\text{m s}^{-1}$
Elementary charge	$e$	1.602 176 565	$10^{-19}$	C
Planck's constant	$h$	6.626 069 57	$10^{-34}$	J s
	$\hbar = h/2\pi$	1.054 571 726	$10^{-34}$	J s
Boltzmann's constant	$k$	1.380 6488	$10^{-23}$	J K <sup>-1</sup>
Avogadro's constant	$N_A$	6.022 141 29	$10^{23}$	mol <sup>-1</sup>
Gas constant	$R = N_A k$	8.314 4621		J K <sup>-1</sup> mol <sup>-1</sup>
Faraday's constant	$F = N_A e$	9.648 533 65	$10^4$	C mol <sup>-1</sup>
Mass				
Electron	$m_e$	9.109 382 91	$10^{-31}$	kg
Proton	$m_p$	1.672 621 777	$10^{-27}$	kg
Neutron	$m_n$	1.674 927 351	$10^{-27}$	kg
Atomic mass constant	$m_u$	1.660 538 921	$10^{-27}$	kg
Vacuum permeability	$\mu_0$	$4\pi^*$	$10^{-7}$	J s <sup>2</sup> C <sup>-2</sup> m <sup>-1</sup>
Vacuum permittivity	$\epsilon_0 = 1/\mu_0 c^2$	8.854 187 817	$10^{-12}$	J <sup>-1</sup> C <sup>2</sup> m <sup>-1</sup>
	$4\pi\epsilon_0$	1.112 650 056	$10^{-10}$	J <sup>-1</sup> C <sup>2</sup> m <sup>-1</sup>
Bohr magneton	$\mu_B = e\hbar/2m_e$	9.274 009 68	$10^{-24}$	J T <sup>-1</sup>
Nuclear magneton	$\mu_N = e\hbar/2m_p$	5.050 783 53	$10^{-27}$	J T <sup>-1</sup>
Proton magnetic moment	$\mu_p$	1.410 606 743	$10^{-26}$	J T <sup>-1</sup>
g-Value of electron	$g_e$	2.002 319 304		
Magnetogyric ratio				
Electron	$\gamma_e = -g_e e/2m_e$	-1.001 159 652	$10^{10}$	C kg <sup>-1</sup>
Proton	$\gamma_p = 2\mu_p/\hbar$	2.675 222 004	$10^8$	C kg <sup>-1</sup>
Bohr radius	$a_0 = 4\pi\epsilon_0\hbar^2/e^2m_e$	5.291 772 109	$10^{-11}$	m
Rydberg constant	$\tilde{R}_\infty = m_e e^4/8h^3 c \epsilon_0^2$	1.097 373 157	$10^5$	cm <sup>-1</sup>
	$hc\tilde{R}_\infty/e$	13.605 692 53		eV
Fine-structure constant	$\alpha = \mu_0 e^2 c/2\hbar$	7.297 352 5698	$10^{-3}$	
	$\alpha^{-1}$	1.370 359 990 74	$10^2$	
Second radiation constant	$c_2 = hc/k$	1.438 777 0	$10^{-2}$	m K
Stefan-Boltzmann constant	$\sigma = 2\pi^5 k^4/15h^3 c^2$	5.670 373	$10^{-8}$	W m <sup>-2</sup> K <sup>-4</sup>
Standard acceleration of free fall	$g$	9.806 65*		m s <sup>-2</sup>
Gravitational constant	$G$	6.673 84	$10^{-11}$	N m <sup>2</sup> kg <sup>-2</sup>

\* Exact value. For current values of the constants, see the National Institute of Standards and Technology (NIST) website.

## Useful relations

At 298.15 K

$RT$	2.4790 kJ mol <sup>-1</sup>	$RT/F$	25.693 mV
$RT \ln 10/F$	59.160 mV	$kT/hc$	207.225 cm <sup>-1</sup>
$kT/e$	25.693 meV	$V_m^\ominus$	2.4790 × 10 <sup>-2</sup> m <sup>3</sup> mol <sup>-1</sup> 24.790 dm <sup>3</sup> mol <sup>-1</sup>

## Selected units\*

1 N	1 kg m s <sup>-2</sup>	1 J	1 kg m <sup>2</sup> s <sup>-2</sup>
1 Pa	1 kg m <sup>-1</sup> s <sup>-2</sup>	1 W	1 J s <sup>-1</sup>
1 V	1 J C <sup>-1</sup>	1 A	1 C s <sup>-1</sup>
1 T	1 kg s <sup>-2</sup> A <sup>-1</sup>	1 P	10 <sup>-1</sup> kg m <sup>-1</sup> s <sup>-1</sup>
1 S	1 Ω <sup>-1</sup> = 1 A V <sup>-1</sup>		

\* For multiples (milli, mega, etc.), see the *Resource section*

## Conversion factors

$$\theta/^{\circ}\text{C} = T/\text{K} - 273.15^*$$

1 eV	1.602 177 × 10 <sup>-19</sup> J	1 cal	4.184* J
	96.485 kJ mol <sup>-1</sup>		
	8065.5 cm <sup>-1</sup>		
1 atm	101.325* kPa	1 cm <sup>-1</sup>	1.9864 × 10 <sup>-23</sup> J
	760* Torr		
1 D	3.335 64 × 10 <sup>-30</sup> C m	1 Å	10 <sup>-10</sup> m*

\* Exact value

## Mathematical relations

$$\pi = 3.141\,592\,653\,59 \dots$$

$$e = 2.718\,281\,828\,46 \dots$$

## Logarithms and exponentials

$$\begin{aligned} \ln x + \ln y + \dots &= \ln xy \dots & \ln x - \ln y &= \ln(x/y) \\ a \ln x &= \ln x^a & \ln x &= \\ & & (\ln 10) \log x &= (2.302\,585 \dots) \\ & & \log x &= \end{aligned}$$

$$e^x e^y e^z \dots = e^{x+y+z+\dots}$$

$$(e^x)^a = e^{ax}$$

$$e^x/e^y = e^{x-y}$$

$$e^{\pm ix} = \cos x \pm i \sin x$$

## Series expansions

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \dots$$

$$\ln(1+x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \dots \quad \ln x = (x-1) - \frac{(x-1)^2}{2} + \frac{(x-1)^3}{3} - \dots$$

$$\frac{1}{1+x} = 1 - x + x^2 - \dots$$

$$\frac{1}{1-x} = 1 + x + x^2 + \dots$$

$$\sin x = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \dots$$

$$\cos x = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \dots$$

## Derivatives; for Integrals, see the *Resource section*

$$d(f+g) = df + dg \quad d(fg) = f dg + g df$$

$$d\frac{f}{g} = \frac{1}{g} df - \frac{f}{g^2} dg \quad \frac{df}{dt} = \frac{df}{dg} \frac{dg}{dt} \quad \text{for } f = f(g(t))$$

$$\left(\frac{\partial y}{\partial x}\right)_z = 1 / \left(\frac{\partial x}{\partial y}\right)_z \quad \left(\frac{\partial y}{\partial x}\right)_z \left(\frac{\partial x}{\partial z}\right)_y \left(\frac{\partial z}{\partial y}\right)_x = -1$$

$$\frac{dx^n}{dx} = nx^{n-1}$$

$$\frac{de^{ax}}{dx} = ae^{ax}$$

$$\frac{d \ln(ax)}{dx} = \frac{1}{x}$$

$$df = g(x, y)dx + h(x, y)dy \text{ is exact if } \left(\frac{\partial g}{\partial y}\right)_x = \left(\frac{\partial h}{\partial x}\right)_y$$

## Greek alphabet\*

A, α	alpha	I, ι	iota	P, ρ	rho
B, β	beta	K, κ	kappa	Σ, σ	sigma
Γ, γ	gamma	Λ, λ	lambda	T, τ	tau
Δ, δ	delta	M, μ	mu	Υ, υ	upsilon
E, ε	epsilon	N, ν	nu	Φ, φ	phi
Z, ζ	zeta	Ξ, ξ	xi	X, χ	chi
H, η	eta	O, o	omicron	Ψ, ψ	psi
Θ, θ	theta	Π, π	pi	Ω, ω	omega

\* Oblique versions (α, β, ...) are used to denote physical observables.



# PREFACE

This new edition is the product of a thorough revision of content and its presentation. Our goal is to make the book even more accessible to students and useful to instructors by enhancing its flexibility. We hope that both categories of user will perceive and enjoy the renewed vitality of the text and the presentation of this demanding but engaging subject.

The text is still divided into three parts, but each chapter is now presented as a series of short and more readily mastered *Topics*. This new structure allows the instructor to tailor the text within the time constraints of the course as omissions will be easier to make, emphases satisfied more readily, and the trajectory through the subject modified more easily. For instance, it is now easier to approach the material either from a ‘quantum first’ or a ‘thermodynamics first’ perspective because it is no longer necessary to take a linear path through chapters. Instead, students and instructors can match the choice of Topics to their learning objectives. We have been very careful not to presuppose or impose a particular sequence, except where it is demanded by common sense.

We open with a *Foundations* chapter, which reviews basic concepts of chemistry and physics used through the text. Part 1 now carries the title *Thermodynamics*. New to this edition is coverage of ternary phase diagrams, which are important in applications of physical chemistry to engineering and materials science. Part 2 (*Structure*) continues to cover quantum theory, atomic and molecular structure, spectroscopy, molecular assemblies, and statistical thermodynamics. Part 3 (*Change*) has lost a chapter dedicated to catalysis, but not the material. Enzyme-catalysed reactions are now in Chapter 20, and heterogeneous catalysis is now part of a new Chapter 22 focused on surface structure and processes.

As always, we have paid special attention to helping students navigate and master this material. Each chapter opens with a brief summary of its Topics. Then each Topic begins with three questions: ‘Why do you need to know this material?’, ‘What is the key idea?’, and ‘What do you need to know already?’. The answers to the third question point to other Topics that we consider appropriate to have studied or at least to refer to as background to the current Topic. The *Checklists* at the end of each

Topic are useful distillations of the most important concepts and equations that appear in the exposition.

We continue to develop strategies to make mathematics, which is so central to the development of physical chemistry, accessible to students. In addition to associating *Mathematical background* sections with appropriate chapters, we give more help with the development of equations: we motivate them, justify them, and comment on the steps taken to derive them. We also added a new feature: *The chemist’s toolkit*, which offers quick and immediate help on a concept from mathematics or physics.

This edition has more worked *Examples*, which require students to organize their thoughts about how to proceed with complex calculations, and more *Brief illustrations*, which show how to use an equation or deploy a concept in a straightforward way. Both have *Self-tests* to enable students to assess their grasp of the material. We have structured the end-of-chapter *Discussion questions*, *Exercises*, and *Problems* to match the grouping of the Topics, but have added Topic- and Chapter-crossing *Integrated activities* to show that several Topics are often necessary to solve a single problem. The *Resource section* has been restructured and augmented by the addition of a list of integrals that are used (and referred to) throughout the text.

We are, of course, alert to the development of electronic resources and have made a special effort in this edition to encourage the use of web-based tools, which are identified in the *Using the book* section that follows this preface. Important among these tools are *Impact* sections, which provide examples of how the material in the chapters is applied in such diverse areas as biochemistry, medicine, environmental science, and materials science.

Overall, we have taken this opportunity to refresh the text thoroughly, making it even more flexible, helpful, and up to date. As ever, we hope that you will contact us with your suggestions for its continued improvement.

PWA, Oxford  
JdeP, Portland

# USING THE BOOK

For the tenth edition of *Atkins' Physical Chemistry* we have tailored the text even more closely to the needs of students. First, the material within each chapter has been re-organized into discrete topics to improve accessibility, clarity, and flex-

ibility. Second, in addition to the variety of learning features already present, we have significantly enhanced the mathematics support by adding new Chemist's toolkit boxes, and checklists of key concepts at the end of each topic.

## Organizing the information

### ► Innovative new structure

Each chapter has been reorganized into short topics, making the text more readable for students and more flexible for instructors. Each topic opens with a comment on why it is important, a statement of the key idea, and a brief summary of the background needed to understand the topic.

#### ► Why do you need to know this material?

Because chemistry is about matter and the changes that it can undergo, both physically and chemically, the properties of matter underlie the entire discussion in this book.

#### ► What is the key idea?

The bulk properties of matter are related to the identities

### ► Notes on good practice

Our *Notes on good practice* will help you avoid making common mistakes. They encourage conformity to the international language of science by setting out the conventions and procedures adopted by the International Union of Pure and Applied Chemistry (IUPAC).

applicable only to perfect gases (and other idealized systems) are labelled, as here, with a number in blue.

*A note on good practice* Although the term 'ideal gas' is almost universally used in place of 'perfect gas', there are reasons for preferring the latter term. In an ideal system the interactions between molecules in a mixture are all the same. In a perfect gas not only are the interactions all the same but they are in fact zero. Few, though, make this useful distinction.

Equation A.5, the **perfect gas equation**, is a summary of three empirical conclusions, namely Boyle's law ( $p \propto 1/V$  at

### ► Resource section

The comprehensive *Resource section* at the end of the book contains a table of integrals, data tables, a summary of conventions about units, and character tables. Short extracts of these tables often appear in the topics themselves, principally to give an idea of the typical values of the physical quantities we are introducing.

## RESOURCE SECTION

#### Contents

1	Common integrals	964
2	Units	965
3	Data	966
4	Character tables	996



## ► Checklist of concepts

A *Checklist of key concepts* is provided at the end of each topic so that you can tick off those concepts which you feel you have mastered.

### Checklist of concepts

- ☐ 1. The **entropy** acts as a signpost of spontaneous change.
- ☐ 2. Entropy change is defined in terms of heat transactions (the **Clausius definition**).
- ☐ 3. The **Boltzmann formula** defines absolute entropies in terms of the number of ways of achieving a configuration.

## Presenting the mathematics

### ► Justifications

Mathematical development is an intrinsic part of physical chemistry, and to achieve full understanding you need to see how a particular expression is obtained and if any assumptions have been made. The *Justifications* are set off from the text to let you adjust the level of detail to meet your current needs and make it easier to review material.

#### Justification 3A.1 Heating accompanying reversible adiabatic expansion

This *Justification* is based on two features of the cycle. One feature is that the two temperatures  $T_h$  and  $T_c$  in eqn 3A.7 lie on the same adiabat in Fig. 3A.7. The second feature is that the energy transferred as heat during the two isothermal stages are

$$q_h = nRT_h \ln \frac{V_B}{V_A} \quad q_c = nRT_c \ln \frac{V_D}{V_C}$$

We now show that the two volume ratios are related in a very simple way. From the relation between temperature and volume for reversible adiabatic processes ( $VT^\gamma = \text{constant}$ , Topic 2D):

### ► Chemist's toolkits

New to the tenth edition, the *Chemist's toolkits* are succinct reminders of the mathematical concepts and techniques that you will need in order to understand a particular derivation being described in the main text.

#### The chemist's toolkit A.1 Quantities and units

The result of a measurement is a **physical quantity** that is reported as a numerical multiple of a unit:

$$\text{physical quantity} = \text{numerical value} \times \text{unit}$$

It follows that units may be treated like algebraic quantities and may be multiplied, divided, and cancelled. Thus, the expression (physical quantity)/unit is the numerical value (a dimensionless quantity) of the measurement in the specified

### ► Mathematical backgrounds

There are six *Mathematical background* sections dispersed throughout the text. They cover in detail the main mathematical concepts that you need to understand in order to be able to master physical chemistry. Each one is located at the end of the chapter to which it is most relevant.

#### Mathematical background 1 Differentiation

Two of the most important mathematical techniques in the physical sciences are differentiation and integration. They occur throughout the subject, and it is essential to be aware of the procedures involved.

##### MB1.1 Differentiation: definitions

Differentiation is concerned with the slopes of functions, such as the rate of change of a variable with time. The formal definition of the **derivative**,  $df/dx$ , of a function  $f(x)$  is



## ► Annotated equations and equation labels

We have annotated many equations to help you follow how they are developed. An annotation can take you across the equals sign: it is a reminder of the substitution used, an approximation made, the terms that have been assumed constant, the integral used, and so on. An annotation can also be a reminder of the significance of an individual term in an expression. We sometimes colour a collection of numbers or symbols to show how they carry from one line to the next. Many of the equations are labelled to highlight their significance.

$$w = -nRT \int_{V_i}^{V_f} \frac{dV}{V} \stackrel{\text{Integral A.2}}{=} -nRT \ln \frac{V_f}{V_i}$$

Perfect gas,  
reversible,  
isothermal

Work of  
expansion (2A.9)

## ► Checklists of equations

You don't have to memorize every equation in the text. A checklist at the end of each topic summarizes the most important equations and the conditions under which they apply.

### Checklist of equations

Property	Equation
Compression factor	$Z = V_m/V_m^\circ$
Virial equation of state	$pV_m = RT(1 + B/V_m + C/V_m^2 + \dots)$
van der Waals equation of state	$p = nRT/(V - nb) - a(n/V)^2$
Reduced variables	$X_r = X_m/X_c$

## Setting up and solving problems

### ► Brief illustrations

A *Brief illustration* shows you how to use equations or concepts that have just been introduced in the text. They help you to learn how to use data, manipulate units correctly, and become familiar with the magnitudes of properties. They are all accompanied by a Self-test question which you can use to monitor your progress.

#### Brief illustration 1C.5 Corresponding states

The critical constants of argon and carbon dioxide are given in Table 1C.2. Suppose argon is at 23 atm and 200 K, its reduced pressure and temperature are then

$$p_r = \frac{23 \text{ atm}}{48.0 \text{ atm}} = 0.48 \quad T_r = \frac{200 \text{ K}}{150.7 \text{ K}} = 1.33$$

For carbon dioxide to be in a corresponding state, its pressure and temperature would need to be

$$p = 0.48 \times (72.9 \text{ atm}) = 35 \text{ atm} \quad T = 1.33 \times 304.2 \text{ K} = 405 \text{ K}$$

**Self-test 1C.6** What would be the corresponding state of ammonia?

Answer: 53 atm, 539 K

## ► Worked examples

Worked *Examples* are more detailed illustrations of the application of the material, which require you to assemble and develop concepts and equations. We provide a suggested method for solving the problem and then implement it to reach the answer. Worked examples are also accompanied by *Self-test* questions.

### Example 3A.2 Calculating the entropy change for a composite process

Calculate the entropy change when argon at 25 °C and 1.00 bar in a container of volume 0.500 dm<sup>3</sup> is allowed to expand to 1.000 dm<sup>3</sup> and is simultaneously heated to 100 °C.

**Method** As remarked in the text, use reversible isothermal expansion to the final volume, followed by reversible heating at constant volume to the final temperature. The entropy change in the first step is given by eqn 3A.16 and that of the second step, provided  $C_V$  is independent of temperature, by eqn 3A.20 (with  $C_V$  in place of  $C_p$ ). In each case we need to

## ► Discussion questions

*Discussion questions* appear at the end of every chapter, where they are organized by topic. These questions are designed to encourage you to reflect on the material you have just read, and to view it conceptually.

## ► Exercises and Problems

*Exercises* and *Problems* are also provided at the end of every chapter, and organized by topic. They prompt you to test your understanding of the topics in that chapter. Exercises are designed as relatively straightforward numerical tests whereas the problems are more challenging. The Exercises come in related pairs, with final numerical answers available on the book's Online Resource Centre for the 'a' questions. Final numerical answers to the odd-numbered problems are also available on the Online Resource Centre.

## ► Integrated activities

At the end of most chapters, you will find questions that cross several topics and chapters, and are designed to help you use your knowledge creatively in a variety of ways. Some of the questions refer to the Living graphs in the Online Resource Centre, which you will find helpful for answering them.

## ► Solutions manuals

Two solutions manuals have been written by Charles Trapp, Marshall Cady, and Carmen Giunta to accompany this book.

The *Student's Solutions Manual* (ISBN 9780198708001) provides full solutions to the 'a' exercises and to the odd-numbered problems.

## TOPIC 3A Entropy

### Discussion questions

**3A.1** The evolution of life requires the organization of a very large number of molecules into biological cells. Does the formation of living organisms violate the Second Law of thermodynamics? State your conclusion clearly and present detailed arguments to support it.

**3A.2** Discuss the significance of the terms 'dispersal' and 'disorder' in the context of the Second Law.

### Exercises

**3A.1(a)** During a hypothetical process, the entropy of a system increases by 125 J K<sup>-1</sup> while the entropy of the surroundings decreases by 125 J K<sup>-1</sup>. Is the process spontaneous?

**3A.1(b)** During a hypothetical process, the entropy of a system increases by 105 J K<sup>-1</sup> while the entropy of the surroundings decreases by 95 J K<sup>-1</sup>. Is the process spontaneous?

**3A.2(a)** A certain ideal heat engine uses water at the triple point as the hot source and an organic liquid as the cold sink. It withdraws 10.00 kJ of heat from the hot source and generates 3.00 kJ of work. What is the temperature of the organic liquid?

**3A.2(b)** A certain ideal heat engine uses water at the triple point as the hot source and an organic liquid as the cold sink. It withdraws 2.71 kJ of heat from the hot source and generates 0.71 kJ of work. What is the temperature of the organic liquid?

The *Instructor's Solutions Manual* provides full solutions to the 'b' exercises and to the even-numbered problems (available to download in the Online Resource Centre for registered adopters of the book only).

# ONLINE RESOURCE CENTRE

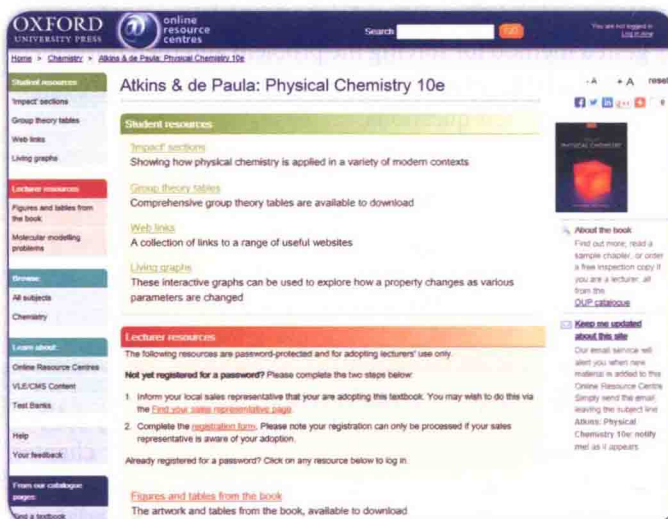
The Online Resource Centre to accompany *Atkins' Physical Chemistry* provides a number of useful teaching and learning resources for students and lecturers.

The site can be accessed at:

[www.oxfordtextbooks.co.uk/orc/pchem10e/](http://www.oxfordtextbooks.co.uk/orc/pchem10e/)

Lecturer resources are available only to registered adopters of the textbook. To register, simply visit the site and follow the link to the registration form.

Student resources are openly available to all, without registration.



## Materials on the online resource centre include:

### 'Impact' sections

'Impact' sections show how physical chemistry is applied in a variety of modern contexts. New for this edition, the Impacts are linked from the text by QR code images. Alternatively, visit the URL displayed next to the QR code image.

### Group theory tables

Comprehensive group theory tables are available to download.

### Web links

This collection of links to a range of useful websites is organized by chapter to aid navigation.

### Figures and tables from the book

Lecturers can find the artwork and tables from the book in ready-to-download format. These may be used for lectures

without charge (but not for commercial purposes without specific permission).

### Molecular modelling problems

PDFs containing molecular modelling problems can be downloaded, designed for use with the Spartan Student™ software. However they can also be completed using any modelling software that allows Hartree-Fock, density functional, and MP2 calculations.

### Living graphs

These interactive graphs can be used to explore how a property changes as various parameters are changed.



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Because we prepared this edition at the same time as its sister volume, *Physical Chemistry: Quanta, matter, and change*, it goes without saying that our colleague on that book, Ron Friedman, has had an unconscious but considerable impact on this text too, and we cannot thank him enough for his contribution to this book. Our warm thanks also go to Charles Trapp, Carmen Giunta, and Marshall Cady who once again have produced the *Solutions manuals* that accompany this book and whose comments led us to make a number of improvements. Kerry Karukstis contributed helpfully to the Impacts that are now on the web.

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## 18 VIII VIIA

Group

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Period 1

1 H  
hydrogen  
1.0079  
1s<sup>1</sup>

2 He  
helium  
4.00  
1s<sup>2</sup>

3 Li  
lithium  
6.94  
2s<sup>1</sup>

4 Be  
beryllium  
9.01  
2s<sup>2</sup>

5 B  
boron  
10.81  
2s<sup>2</sup>2p<sup>1</sup>

6 C  
carbon  
12.01  
2s<sup>2</sup>2p<sup>2</sup>

7 N  
nitrogen  
14.01  
2s<sup>2</sup>2p<sup>3</sup>

8 O  
oxygen  
16.00  
2s<sup>2</sup>2p<sup>4</sup>

9 F  
fluorine  
19.00  
2s<sup>2</sup>2p<sup>5</sup>

10 Ne  
neon  
20.18  
2s<sup>2</sup>2p<sup>6</sup>

11 Na  
sodium  
22.99  
3s<sup>1</sup>

12 Mg  
magnesium  
24.31  
3s<sup>2</sup>

13 Al  
aluminum  
26.98  
3s<sup>2</sup>3p<sup>1</sup>

14 Si  
silicon  
28.09  
3s<sup>2</sup>3p<sup>2</sup>

15 P  
phosphorus  
30.97  
3s<sup>2</sup>3p<sup>3</sup>

16 S  
sulfur  
32.06  
3s<sup>2</sup>3p<sup>4</sup>

17 Cl  
chlorine  
35.45  
3s<sup>2</sup>3p<sup>5</sup>

18 Ar  
argon  
39.95  
3s<sup>2</sup>3p<sup>6</sup>

19 K  
potassium  
39.10  
4s<sup>1</sup>

20 Ca  
calcium  
40.08  
4s<sup>2</sup>

21 Sc  
scandium  
44.96  
3d<sup>1</sup>4s<sup>2</sup>

22 Ti  
titanium  
47.87  
3d<sup>2</sup>4s<sup>2</sup>

23 V  
vanadium  
50.94  
3d<sup>3</sup>4s<sup>2</sup>

24 Cr  
chromium  
52.00  
3d<sup>5</sup>4s<sup>1</sup>

25 Mn  
manganese  
54.94  
3d<sup>5</sup>4s<sup>2</sup>

26 Fe  
iron  
55.84  
3d<sup>6</sup>4s<sup>2</sup>

27 Co  
cobalt  
58.93  
3d<sup>7</sup>4s<sup>2</sup>

28 Ni  
nickel  
58.69  
3d<sup>8</sup>4s<sup>2</sup>

29 Cu  
copper  
63.55  
3d<sup>10</sup>4s<sup>1</sup>

30 Zn  
zinc  
65.41  
3d<sup>10</sup>4s<sup>2</sup>

31 Ga  
gallium  
69.72  
4s<sup>2</sup>4p<sup>1</sup>

32 Ge  
germanium  
72.64  
4s<sup>2</sup>4p<sup>2</sup>

33 As  
arsenic  
74.92  
4s<sup>2</sup>4p<sup>3</sup>

34 Se  
selenium  
78.96  
4s<sup>2</sup>4p<sup>4</sup>

35 Br  
bromine  
79.90  
4s<sup>2</sup>4p<sup>5</sup>

36 Kr  
krypton  
83.80  
4s<sup>2</sup>4p<sup>6</sup>

37 Rb  
rubidium  
85.47  
5s<sup>1</sup>

38 Sr  
strontium  
87.62  
5s<sup>2</sup>

39 Y  
yttrium  
88.91  
4d<sup>1</sup>5s<sup>2</sup>

40 Zr  
zirconium  
91.22  
4d<sup>2</sup>5s<sup>2</sup>

41 Nb  
niobium  
92.91  
4d<sup>4</sup>5s<sup>1</sup>

42 Mo  
molybdenum  
95.94  
4d<sup>5</sup>5s<sup>1</sup>

43 Tc  
technetium  
(98)  
4d<sup>5</sup>5s<sup>2</sup>

44 Ru  
ruthenium  
101.07  
4d<sup>7</sup>5s<sup>1</sup>

45 Rh  
rhodium  
102.90  
4d<sup>8</sup>5s<sup>1</sup>

46 Pd  
palladium  
106.42  
4d<sup>10</sup>

47 Ag  
silver  
107.87  
4d<sup>10</sup>5s<sup>1</sup>

48 Cd  
cadmium  
112.41  
4d<sup>10</sup>5s<sup>2</sup>

49 In  
indium  
114.82  
5s<sup>2</sup>5p<sup>1</sup>

50 Sn  
tin  
118.71  
5s<sup>2</sup>5p<sup>2</sup>

51 Sb  
antimony  
121.76  
5s<sup>2</sup>5p<sup>3</sup>

52 Te  
tellurium  
127.60  
5s<sup>2</sup>5p<sup>4</sup>

53 I  
iodine  
126.90  
5s<sup>2</sup>5p<sup>5</sup>

54 Xe  
xenon  
131.29  
5s<sup>2</sup>5p<sup>6</sup>

55 Cs  
cesium  
132.91  
6s<sup>1</sup>

56 Ba  
barium  
137.33  
6s<sup>2</sup>

57 La  
lanthanum  
138.91  
5d<sup>1</sup>6s<sup>2</sup>

58 Ce  
cerium  
140.12  
4f<sup>1</sup>5d<sup>1</sup>6s<sup>2</sup>

59 Pr  
praseodymium  
140.91  
4f<sup>3</sup>6s<sup>2</sup>

60 Nd  
neodymium  
144.24  
4f<sup>4</sup>6s<sup>2</sup>

61 Pm  
promethium  
(145)  
4f<sup>5</sup>6s<sup>2</sup>

62 Sm  
samarium  
150.36  
4f<sup>6</sup>6s<sup>2</sup>

63 Eu  
europium  
151.96  
4f<sup>7</sup>6s<sup>2</sup>

64 Gd  
gadolinium  
157.25  
4f<sup>7</sup>5d<sup>1</sup>6s<sup>2</sup>

65 Tb  
terbium  
158.93  
4f<sup>9</sup>6s<sup>2</sup>

66 Dy  
dysprosium  
162.50  
4f<sup>10</sup>6s<sup>2</sup>

67 Ho  
holmium  
164.93  
4f<sup>11</sup>6s<sup>2</sup>

68 Er  
erbium  
167.26  
4f<sup>12</sup>6s<sup>2</sup>

69 Tm  
thulium  
168.93  
4f<sup>13</sup>6s<sup>2</sup>

70 Yb  
ytterbium  
173.04  
4f<sup>14</sup>6s<sup>2</sup>

71 Lu  
lutetium  
174.97  
5d<sup>1</sup>6s<sup>2</sup>

72 Hf  
hafnium  
178.49  
5d<sup>2</sup>6s<sup>2</sup>

73 Ta  
tantalum  
180.95  
5d<sup>3</sup>6s<sup>2</sup>

74 W  
tungsten  
183.84  
5d<sup>4</sup>6s<sup>2</sup>

75 Re  
rhenium  
186.21  
5d<sup>5</sup>6s<sup>2</sup>

76 Os  
osmium  
190.23  
5d<sup>6</sup>6s<sup>2</sup>

77 Ir  
iridium  
192.22  
5d<sup>7</sup>6s<sup>2</sup>

78 Pt  
platinum  
195.08  
5d<sup>9</sup>6s<sup>1</sup>

79 Au  
gold  
196.97  
5d<sup>10</sup>6s<sup>1</sup>

80 Hg  
mercury  
200.59  
5d<sup>10</sup>6s<sup>2</sup>

81 Tl  
thallium  
204.38  
6s<sup>2</sup>6p<sup>1</sup>

82 Pb  
lead  
207.2  
6s<sup>2</sup>6p<sup>2</sup>

83 Bi  
bismuth  
208.98  
6s<sup>2</sup>6p<sup>3</sup>

84 Po  
polonium  
(209)  
6s<sup>2</sup>6p<sup>4</sup>

85 At  
astatine  
(210)  
6s<sup>2</sup>6p<sup>5</sup>

86 Rn  
radon  
(222)  
6s<sup>2</sup>6p<sup>6</sup>

87 Fr  
francium  
(223)  
7s<sup>1</sup>

88 Ra  
radium  
(226)  
7s<sup>2</sup>

89 Ac  
actinium  
(227)  
6d<sup>1</sup>7s<sup>2</sup>

90 Th  
thorium  
232.04  
6d<sup>2</sup>7s<sup>2</sup>

91 Pa  
protactinium  
231.04  
5f<sup>2</sup>6d<sup>1</sup>7s<sup>2</sup>

92 U  
uranium  
238.03  
5f<sup>3</sup>6d<sup>1</sup>7s<sup>2</sup>

93 Np  
neptunium  
(237)  
5f<sup>4</sup>6d<sup>1</sup>7s<sup>2</sup>

94 Pu  
plutonium  
(244)  
5f<sup>7</sup>7s<sup>2</sup>

95 Am  
americium  
(243)  
5f<sup>7</sup>7s<sup>2</sup>

96 Cm  
curium  
(247)  
5f<sup>7</sup>6d<sup>1</sup>7s<sup>2</sup>

97 Bk  
berkelium  
(247)  
5f<sup>9</sup>7s<sup>2</sup>

98 Cf  
californium  
(251)  
5f<sup>10</sup>7s<sup>2</sup>

99 Es  
einsteinium  
(252)  
5f<sup>11</sup>7s<sup>2</sup>

100 Fm  
fermium  
(257)  
5f<sup>12</sup>7s<sup>2</sup>

101 Md  
mendelevium  
(258)  
5f<sup>13</sup>7s<sup>2</sup>

102 No  
nobelium  
(259)  
5f<sup>14</sup>7s<sup>2</sup>

103 Lr  
lawrencium  
(262)  
6d<sup>1</sup>7s<sup>2</sup>

104 Rf  
rutherfordium  
(261)  
6d<sup>7</sup>7s<sup>2</sup>

105 Db  
dubnium  
(262)  
6d<sup>7</sup>7s<sup>2</sup>

106 Sg  
seaborgium  
(263)  
6d<sup>7</sup>7s<sup>2</sup>

107 Bh  
bohrium  
(262)  
6d<sup>8</sup>7s<sup>2</sup>

108 Hs  
hassium  
(265)  
6d<sup>9</sup>7s<sup>2</sup>

109 Mt  
meitnerium  
(266)  
6d<sup>7</sup>7s<sup>2</sup>

110 Ds  
darmstadtium  
(271)  
6d<sup>7</sup>7s<sup>2</sup>

111 Rg  
roentgenium  
(272)  
6d<sup>7</sup>7s<sup>2</sup>

112 Cn  
copernicium  
?  
6d<sup>10</sup>7s<sup>2</sup>

113 Fv  
flerovium  
?  
7s<sup>2</sup>7p<sup>2</sup>

114 Lv  
livermorium  
?  
7s<sup>2</sup>7p<sup>4</sup>

115

116

117

118

Period 2

Period 3

Period 4

Period 5

Period 6

Period 7

IA

II

IIA

IIIB

IVB

VB

VIB

VIIA

VIIIB

IB

IIB

IIIA

IVA

VA

VIA

VII

VIIA

Period

1

2

3

4

5

6

7

Molar masses (atomic weights) quoted to the number of significant figures given here can be regarded as typical of most naturally occurring samples

Molar masses (atomic weights) quoted to the number of significant figures given here can be regarded as typical of most naturally occurring samples

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