Preface

The only way to learn physics is to do physics. However, almost all physics textbooks leave a huge gap between the level of the problems that they solve as examples, and the level of the problems that they assign to the students to do as homework and to thereby learn the physics. This book attempts to fill this gap for the first quantum mechanics course which our students find particularly difficult.

The level of our solved problems is the same as that of the solutions that we expect from our students. We try very hard not to leave out any of the "unnecessary" or "obvious" steps until the concepts are well rooted. Clearly no book can show you how to solve every problem. Our goal was to help you learn how to solve a representative subset of all beginning quantum mechanics problems.

We tried to select a minimum number of core concepts that all physicists would agree are essential for beginning quantum mechanics. We hope that you will find it possible to bridge the gap between these problems and the other problems that you want to solve. Most of our students have been able to make the necessary quantum leap.

There is a physics joke about the stages of learning quantum mechanics:

(1) You don't know what it means, you don't know how to calculate anything, and it doesn't bother you.
(2) You don't know what it means, you don't know how to calculate anything, and it bothers you.
(3) You don't know what it means, you know how to calculate things, and it bothers you.
(4) You don't know what it means, you know how to calculate things, and it doesn't bother you.

This book has been designed to help you learn to calculate. Our goal is to get you to stage (4). However, this is not a conventional quantum mechanics textbook, rather we recommend that you use it with a standard textbook for your quantum course or for self study.

We show you how to calculate by example: first we provide a set of paradigmatic problems and their complete solutions. By studying these detailed solutions, and by then using them to solve the additional practice problems that we provide, our students have been able to master the fundamentals of quantum calculations. We consider these fundamentals to include the Dirac, Schrödinger, and Heisenberg formulations, which we treat with equal footing throughout the text.

Learning how to calculate is essential because the only language in which we can express, analyze, and discuss quantum mechanics is mathematics. As Willis Lamb put it in 1969:

> "I have taught graduate courses in quantum mechanics at Columbia, Stanford, Oxford, and Yale, and for almost all of them have dealt with measurement in the following manner. On beginning the lectures I told the students, 'You must first learn the rules of calculation in quantum mechanics, and then I will discuss the theory of measurement and discuss the meaning of the subject.' Almost invariably, the time allotted to the course ran out before I had to fulfill my promise."

As Weinberg put it:

> "There is a good deal of confusion about this, because quantum mechanics can seem eerie if described in ordinary language."

According to Mermin, most physicists are at stage (3) or stage (4):

> "...contemporary physicists come in two varieties. Type 1 physicists are bothered by EPR and Bell's Theorem. Type 2 (the majority) are not, but one has to distinguish two sub-varieties. Type 2a physicists explain why they are not bothered. Their explanations tend either to miss the point entirely (like Born's to Einstein) or to contain physical assertions that can be shown to be false. Type 2b are not bothered and refuse to explain why."

Of course the goal of physics is to reach stage (5): to know what it means to be able to calculate everything and not to be bothered by the way the universe works. Unfortunately, it has become traditional to teach quantum mechanics as a subject of great mystery that no one understands:

> "If quantum mechanics hasn't profoundly shocked you, you cannot have understood it yet." (Bohr)

> There is no reality in the absence of observation. (The Copenhagen Interpretation)

> "Shut up and calculate." (Mermin's operational version of the Copenhagen Interpretation)

It seems crazy to us to continue to teach generation after generation of our students that they will not be able to understand quantum mechanics. All physicists eventually understand quantum mechanics to some extent. Of course, there are still open questions about the meaning of quantum mechanics; for example, Einstein's reservations about the meaning of quantum mechanics are legendary:

> "I recall that during one walk Einstein suddenly stopped, turned to me and asked whether I really believed that the moon exists only when I look at it. The rest of this walk was devoted to a discussion of what a physicist should mean by the term *to exist*." (Pais)

> "Quantum mechanics is very impressive. But an inner voice tells me that it is not yet the real thing. The theory yields a lot, but it hardly brings us any closer to the secret of the Old One. In any case I am convinced that He doesn't play dice." (Einstein)

> "What nature demands from us is not a quantum theory or a wave theory; rather, nature demands from us a synthesis of these two views which thus far has exceeded the mental powers of physicists. I cannot seriously believe in the quantum theory because the theory is incompatible with the principle that physics is to represent reality in space and time, without spooky actions at a distance." (Einstein)

Even today, the "mysteries" of quantum mechanics continue to echo and to morph:

> "No theory of reality compatible with quantum theory can require spatially separate events to be independent." (Bell)

> "…experiments have now shown that what bothered Einstein is not a debatable point but the observed behavior of the real world." (Mermin)

> "Anybody who's not bothered by Bell's theorem has to have rocks in his head." (Wightman)

> "Evidently, God not only plays dice but plays blind-folded, and, at

> times, throws them where you can't see them.” (Hawking)
>
> “And let no one use the Einstein-Podolsky-Rosen experiment to claim that information can be transmitted faster than light, or to postulate any ‘quantum interconnectedness’ between separate consciousnesses. Both are baseless. Both are mysticism. Both are moonshine.” (Wheeler)
>
> “Niels Bohr brainwashed a whole generation of theorists into thinking that the job (interpreting quantum theory) was done 50 years ago.” (Gell-Mann)

The formalism of quantum theory leads to results that agree with experiment with great accuracy and covers an extremely wide range of phenomena. As yet there are no experimental indications of any domain in which it might break down. Nevertheless, there still remain a number of basic questions concerning its fundamental significance which are obscure and confused.

> “Quantum mechanics, that mysterious, confusing discipline, which none of us really understands but which we know how to use.” (Bohm and Hiley)
>
> “Einstein said that if quantum mechanics is right, then the world is crazy … Well, Einstein was right. The world is crazy.” (Greenberger)
>
> “Most physicists are very naive; most still believe in real waves or real particles.” (Zeilinger)

So, is there a problem, or isn't there? Note Feynman’s changing perspective on this question:

> “…I think I can safely say that nobody understands quantum mechanics. So do not take the lecture too seriously, feeling that you have to understand in terms of some model what I am going to describe, but just relax and enjoy it. I am going to tell you what nature behaves like. If you will simply admit that she maybe does behave like this, you will find her a delightful, entrancing thing. Do not keep saying to yourself, if you can possibly avoid it, ‘But how can it be like that?’ because you will get ‘down the drain’ into a blind alley from which nobody has yet escaped. Nobody knows how it can be like that.” (1964)

> "We have always had a great deal of difficulty understanding the world view that quantum mechanics represents. At least I do, because I'm an old enough man that I haven't got to the point that this stuff is obvious to me. Okay, I still get nervous about it... You know how it always is, every new idea, it takes a generation or two until it is obvious that there's no real problem. I cannot define the real problem, therefore I suspect there's no real problem, but I'm not sure there's no real problem." (1982)

Quantum mechanics demands the most extraordinary change in our scientific world view of any physical theory. As a boy, Feynman studied Calculus Made Easy by S.P. Thompson that begins, "What one fool can do, another can." He dedicated his book QED: The Strange Theory of Light and Matter to his readers with similar words: "What one fool can understand, another can." In a similar spirit, we hope that this book will help you start on your own journey towards understanding quantum mechanics.

As Feynman concludes his Lectures on Physics:

> "The quantum mechanics which was discovered in 1926 has had nearly 40 years of development, and rather suddenly it has begun to be exploited in many practical and real ways. I am sorry to say, gentlemen, that to participate in this adventure it is absolutely imperative that you learn quantum mechanics as soon as possible. I wanted most to give you some appreciation of the wonderful world and the physicist's way of looking at it, which, I believe, is a major part of the true culture of our times. Perhaps you will not only have some appreciation of this culture; it is even possible that you may want to join in the greatest adventure that the human mind has ever begun."

Perhaps it is only a matter of time:

> "A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it." (Planck)

But surely, inevitably, the present drive for quantum computation and quantum cryptography will continue to force us towards a more realistic experimental practical understanding of quantum mechanics. You are the new generation – you are in the best of company -- welcome to the inquiry!

Recommended Texts on Mathematical Methods

G. Arfken, *Mathematical Methods for Physicists, Third Edition*, (Academic Press, Inc.), 1985.

M.L. Boas, *Mathematical Methods in the Physical Sciences, Second Edition*, (John Wiley & Sons), 1983.

A.G. Hamilton, *Linear Algebra, An Introduction with Concurrent Examples*, (Cambridge University Press), 1989.