

# 1 THE WAVE FUNCTION

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## 1.1 THE SCHRÖDINGER EQUATION

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Imagine a particle of mass  $m$ , constrained to move along the  $x$  axis, subject to some specified force  $F(x, t)$  (Figure 1.1). The program of *classical* mechanics is to determine the position of the particle at any given time:  $x(t)$ . Once we know that, we can figure out the velocity ( $v = dx/dt$ ), the momentum ( $p = mv$ ), the kinetic energy ( $T = (1/2)mv^2$ ), or any other dynamical variable of interest. And how do we go about determining  $x(t)$ ? We apply Newton's second law:  $F = ma$ . (For *conservative* systems—the only kind we shall consider, and, fortunately, the only kind that *occur* at the microscopic level—the force can be expressed as the derivative of a potential energy function,<sup>1</sup>  $F = -\partial V/\partial x$ , and Newton's law reads  $m d^2x/dt^2 = -\partial V/\partial x$ .) This, together with appropriate initial conditions (typically the position and velocity at  $t = 0$ ), determines  $x(t)$ .

Quantum mechanics approaches this same problem quite differently. In this case what we're looking for is the particle's **wave function**,  $\Psi(x, t)$ , and we get it by solving the **Schrödinger equation**:

$$i\hbar \frac{\partial \Psi}{\partial t} = -\frac{\hbar^2}{2m} \frac{\partial^2 \Psi}{\partial x^2} + V\Psi. \quad (1.1)$$

Here  $i$  is the square root of  $-1$ , and  $\hbar$  is Planck's constant—or rather, his *original* constant ( $h$ ) divided by  $2\pi$ :

$$\hbar = \frac{h}{2\pi} = 1.054573 \times 10^{-34} \text{ J s}. \quad (1.2)$$

The Schrödinger equation plays a role logically analogous to Newton's second law: Given suitable initial conditions (typically,  $\Psi(x, 0)$ ), the Schrödinger equation determines  $\Psi(x, t)$  for all future time, just as, in classical mechanics, Newton's law determines  $x(t)$  for all future time.<sup>2</sup>

## 1.2 THE STATISTICAL INTERPRETATION

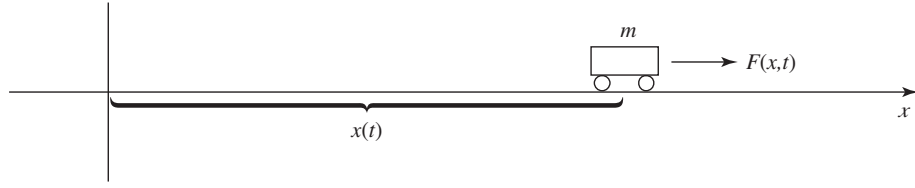
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But what exactly *is* this “wave function,” and what does it do for you once you've *got* it? After all, a particle, by its nature, is localized at a point, whereas the wave function (as its name

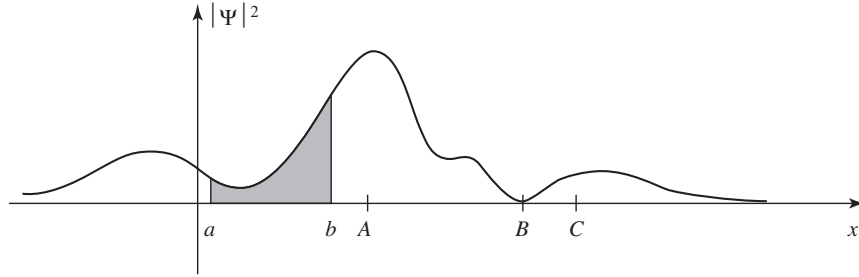
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<sup>1</sup> Magnetic forces are an exception, but let's not worry about them just yet. By the way, we shall assume throughout this book that the motion is nonrelativistic ( $v \ll c$ ).

<sup>2</sup> For a delightful first-hand account of the origins of the Schrödinger equation see the article by Felix Bloch in *Physics Today*, December 1976.



**Figure 1.1:** A “particle” constrained to move in one dimension under the influence of a specified force.



**Figure 1.2:** A typical wave function. The shaded area represents the probability of finding the particle between  $a$  and  $b$ . The particle would be relatively likely to be found near  $A$ , and unlikely to be found near  $B$ .

suggests) is spread out in space (it’s a function of  $x$ , for any given  $t$ ). How can such an object represent the state of a *particle*? The answer is provided by Born’s **statistical interpretation**, which says that  $|\Psi(x, t)|^2$  gives the *probability* of finding the particle at point  $x$ , at time  $t$ —or, more precisely,<sup>3</sup>

$$\int_a^b |\Psi(x, t)|^2 dx = \left\{ \begin{array}{l} \text{probability of finding the particle} \\ \text{between } a \text{ and } b, \text{ at time } t. \end{array} \right\} \quad (1.3)$$

Probability is the *area* under the graph of  $|\Psi|^2$ . For the wave function in Figure 1.2, you would be quite likely to find the particle in the vicinity of point  $A$ , where  $|\Psi|^2$  is large, and relatively *unlikely* to find it near point  $B$ .

The statistical interpretation introduces a kind of **indeterminacy** into quantum mechanics, for even if you know everything the theory has to tell you about the particle (to wit: its wave function), still you cannot predict with certainty the outcome of a simple experiment to measure its position—all quantum mechanics has to offer is *statistical* information about the *possible* results. This indeterminacy has been profoundly disturbing to physicists and philosophers alike, and it is natural to wonder whether it is a fact of nature, or a defect in the theory.

Suppose I *do* measure the position of the particle, and I find it to be at point  $C$ .<sup>4</sup> *Question:* Where was the particle just *before* I made the measurement? There are three plausible answers

<sup>3</sup> The wave function itself is complex, but  $|\Psi|^2 = \Psi^* \Psi$  (where  $\Psi^*$  is the complex conjugate of  $\Psi$ ) is real and non-negative—as a probability, of course, *must* be.

<sup>4</sup> Of course, no measuring instrument is perfectly precise; what I *mean* is that the particle was found *in the vicinity* of  $C$ , as defined by the precision of the equipment.

to this question, and they serve to characterize the main schools of thought regarding quantum indeterminacy:

1. The **realist** position: *The particle was at C*. This certainly seems reasonable, and it is the response Einstein advocated. Note, however, that if this is true then quantum mechanics is an *incomplete* theory, since the particle *really was* at *C*, and yet quantum mechanics was unable to tell us so. To the realist, indeterminacy is not a fact of nature, but a reflection of our ignorance. As d’Espagnat put it, “the position of the particle was never indeterminate, but was merely unknown to the experimenter.”<sup>5</sup> Evidently  $\Psi$  is not the whole story—some additional information (known as a **hidden variable**) is needed to provide a complete description of the particle.

2. The **orthodox** position: *The particle wasn’t really anywhere*. It was the act of measurement that forced it to “take a stand” (though how and why it decided on the point *C* we dare not ask). Jordan said it most starkly: “Observations not only *disturb* what is to be measured, they *produce* it . . . We *compel* [the particle] to assume a definite position.”<sup>6</sup> This view (the so-called **Copenhagen interpretation**), is associated with Bohr and his followers. Among physicists it has always been the most widely accepted position. Note, however, that if it is correct there is something very peculiar about the act of measurement—something that almost a century of debate has done precious little to illuminate.

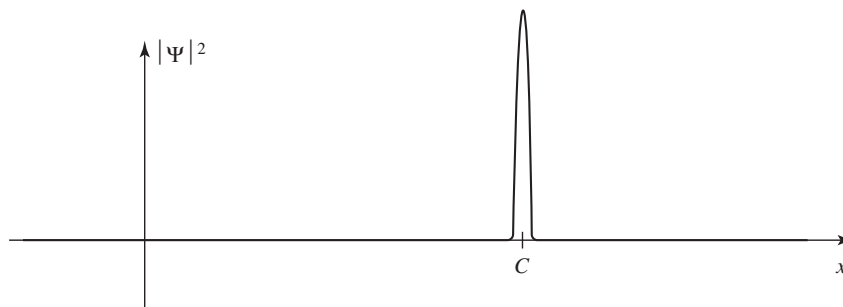
3. The **agnostic** position: *Refuse to answer*. This is not quite as silly as it sounds—after all, what sense can there be in making assertions about the status of a particle *before* a measurement, when the only way of knowing whether you were right is precisely to *make* a measurement, in which case what you get is no longer “before the measurement”? It is metaphysics (in the pejorative sense of the word) to worry about something that cannot, by its nature, be tested. Pauli said: “One should no more rack one’s brain about the problem of whether something one cannot know anything about exists all the same, than about the ancient question of how many angels are able to sit on the point of a needle.”<sup>7</sup> For decades this was the “fall-back” position of most physicists: they’d try to sell you the orthodox answer, but if you were persistent they’d retreat to the agnostic response, and terminate the conversation.

Until fairly recently, all three positions (realist, orthodox, and agnostic) had their partisans. But in 1964 John Bell astonished the physics community by showing that it makes an *observable* difference whether the particle had a precise (though unknown) position prior to

<sup>5</sup> Bernard d’Espagnat, “The Quantum Theory and Reality” (*Scientific American*, November 1979, p. 165).

<sup>6</sup> Quoted in a lovely article by N. David Mermin, “Is the moon there when nobody looks?” (*Physics Today*, April 1985, p. 38).

<sup>7</sup> *Ibid.*, p. 40.



**Figure 1.3:** Collapse of the wave function: graph of  $|\Psi|^2$  immediately *after* a measurement has found the particle at point  $C$ .

the measurement, or not. Bell’s discovery effectively eliminated agnosticism as a viable option, and made it an *experimental* question whether 1 or 2 is the correct choice. I’ll return to this story at the end of the book, when you will be in a better position to appreciate Bell’s argument; for now, suffice it to say that the experiments have decisively confirmed the orthodox interpretation:<sup>8</sup> a particle simply does not have a precise position prior to measurement, any more than the ripples on a pond do; it is the measurement process that insists on one particular number, and thereby in a sense *creates* the specific result, limited only by the statistical weighting imposed by the wave function.

What if I made a *second* measurement, immediately after the first? Would I get  $C$  again, or does the act of measurement cough up some completely new number each time? On this question everyone is in agreement: A repeated measurement (on the same particle) must return the same value. Indeed, it would be tough to prove that the particle was really found at  $C$  in the first instance, if this could not be confirmed by immediate repetition of the measurement. How does the orthodox interpretation account for the fact that the second measurement is bound to yield the value  $C$ ? It must be that the first measurement radically alters the wave function, so that it is now sharply peaked about  $C$  (Figure 1.3). We say that the wave function **collapses**, upon measurement, to a spike at the point  $C$  (it soon spreads out again, in accordance with the Schrödinger equation, so the second measurement must be made quickly). There are, then, two entirely distinct kinds of physical processes: “ordinary” ones, in which the wave function evolves in a leisurely fashion under the Schrödinger equation, and “measurements,” in which  $\Psi$  suddenly and discontinuously collapses.<sup>9</sup>

<sup>8</sup> This statement is a little too strong: there exist viable nonlocal hidden variable theories (notably David Bohm’s), and other formulations (such as the **many worlds** interpretation) that do not fit cleanly into any of my three categories. But I think it is wise, at least from a pedagogical point of view, to adopt a clear and coherent platform at this stage, and worry about the alternatives later.

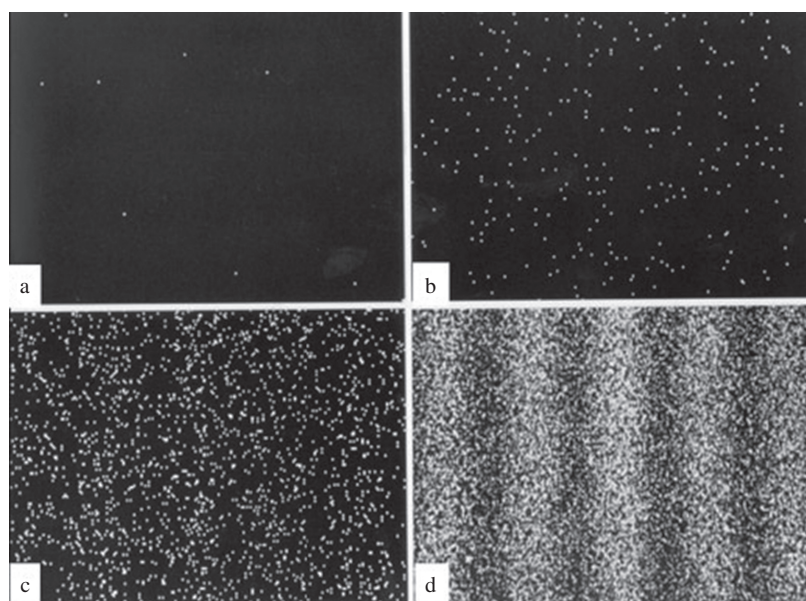
<sup>9</sup> The role of measurement in quantum mechanics is so critical and so bizarre that you may well be wondering what precisely *constitutes* a measurement. I’ll return to this thorny issue in the Afterword; for the moment let’s take the naive view: a measurement is the kind of thing that a scientist in a white coat does in the laboratory, with rulers, stopwatches, Geiger counters, and so on.

**Example 1.1**

**Electron Interference.** I have asserted that particles (electrons, for example) have a wave nature, encoded in  $\Psi$ . How might we check this, in the laboratory?

The classic signature of a wave phenomenon is *interference*: two waves *in phase* interfere constructively, and out of phase they interfere destructively. The wave nature of light was confirmed in 1801 by Young’s famous double-slit experiment, showing interference “fringes” on a distant screen when a monochromatic beam passes through two slits. If essentially the same experiment is done with *electrons*, the same pattern develops,<sup>10</sup> confirming the wave nature of electrons.

Now suppose we decrease the intensity of the electron beam, until only one electron is present in the apparatus at any particular time. According to the statistical interpretation each electron will produce a spot on the screen. Quantum mechanics cannot predict the precise *location* of that spot—all it can tell us is the *probability* of a given electron landing at a particular place. But if we are patient, and wait for a hundred thousand electrons—one at a time—to make the trip, the accumulating spots reveal the classic two-slit interference pattern (Figure 1.4).<sup>11</sup>



**Figure 1.4:** Build-up of the electron interference pattern. (a) Eight electrons, (b) 270 electrons, (c) 2000 electrons, (d) 160,000 electrons. Reprinted courtesy of the Central Research Laboratory, Hitachi, Ltd., Japan.

<sup>10</sup> Because the wavelength of electrons is typically very small, the slits have to be extremely close together. Historically, this was first achieved by Davisson and Germer, in 1925, using the atomic layers in a crystal as “slits.” For an interesting account, see R. K. Gehrenbeck, *Physics Today*, January 1978, page 34.

<sup>11</sup> See Tonomura et al., *American Journal of Physics*, Volume 57, Issue 2, pp. 117–120 (1989), and the amazing associated video at [www.hitachi.com/rd/portal/highlight/quantum/doubleslit/](http://www.hitachi.com/rd/portal/highlight/quantum/doubleslit/). This experiment can now be done with much more massive particles, including “Bucky-balls”; see M. Arndt, et al., *Nature* **40**, 680 (1999). Incidentally, the same thing can be done with light: turn the intensity so low that only one “photon” is present at a time and you get an identical point-by-point assembly of the interference pattern. See R. S. Aspdén, M. J. Padgett, and G. C. Spalding, *Am. J. Phys.* **84**, 671 (2016).

Of course, if you close off one slit, or somehow contrive to detect which slit each electron passes through, the interference pattern disappears; the wave function of the emerging particle is now entirely different (in the first case because the boundary conditions for the Schrödinger equation have been changed, and in the second because of the collapse of the wave function upon measurement). But with both slits open, and no interruption of the electron in flight, each electron interferes with itself; it didn't pass through one slit or the other, but through both at once, just as a water wave, impinging on a jetty with two openings, interferes with itself. There is nothing mysterious about this, once you have accepted the notion that particles obey a wave equation. The truly *astonishing* thing is the blip-by-blip assembly of the pattern. In any classical wave theory the pattern would develop smoothly and continuously, simply getting more intense as time goes on. The quantum process is more like the pointillist painting of Seurat: The picture emerges from the cumulative contributions of all the individual dots.<sup>12</sup>

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<sup>12</sup> I think it is important to distinguish things like interference and diffraction that would hold for any wave theory from the uniquely quantum mechanical features of the measurement process, which derive from the statistical interpretation.