

# A Phase Space

Current use of the term *phase space* in nonlinear science is conveniently exemplified by (2.1) – the Lorenz equations – and the corresponding sketch of Fig. 2.1. This is a *three-dimensional* phase space because there are three first order ODEs involving three *dependent variables* ( $x$ ,  $y$  and  $z$ ) governing the state of the system at time  $t$  (the *independent variable*), which can be indicated as a *phase point*

$$\mathbf{P} = (x, y, z) ,$$

in this space. The functions on the right-hand sides (RHS) of (2.1) then give the components of a “velocity” vector

$$\mathbf{V} = \left( \frac{dx}{dt}, \frac{dy}{dt}, \frac{dz}{dt} \right) ,$$

which determines how fast the phase point is moving in the phase space and in what direction. From a geometrical perspective, (2.1) show how  $\mathbf{V}$  is computed from a position vector; thus

$$\mathbf{P} \xrightarrow{(2.1)} \mathbf{V} .$$

Integrating (2.1) then indicates where the phase point will be – or what the state of the system will be – at some future time, thus mapping out a *solution trajectory* or *orbit* in the phase space.

Equations (2.1) are called *autonomous* because the RHS functions depend only on the position of the phase point, and not, for example, on the time  $t$  (or on the positions of the celestial bodies, as the astrologers would suggest). Assuming that the RHS functions are uniquely defined, then trajectories cannot cross, for this would be a contradiction.

Chaotic trajectories in a phase space of two dimensions, called a *phase plane*. In analyzing dynamics on a phase plane, we begin with two equations of the form

$$\frac{dx}{dt} = F(x, y) , \quad \frac{dy}{dt} = G(x, y) ,$$

and the first step is to find *singular points* (SPs) where the velocity vector  $\mathbf{V}$  is zero. Singular points  $(x_0, y_0)$  evidently satisfy  $F(x_0, y_0) = 0$  and  $G(x_0, y_0) = 0$ , which can be determined either analytically or numerically.

Having found a singular point, it is interesting to ask how the solution trajectory behaves in the vicinity of this SP. This can be answered by noting that as  $\mathbf{V} = 0$  at a SP, it must have small magnitude nearby; thus the governing equations can be written as

$$\begin{aligned}\frac{dx}{dt} &= ax + by + \text{higher order terms}, \\ \frac{dy}{dt} &= cx + dy + \text{higher order terms},\end{aligned}$$

where  $a \equiv \partial F/\partial x|_{x_0, y_0}$ ,  $b \equiv \partial F/\partial y|_{x_0, y_0}$ ,  $c \equiv \partial G/\partial x|_{x_0, y_0}$  and  $d \equiv \partial G/\partial y|_{x_0, y_0}$ . As the “higher-order terms” involve products or powers of  $x$  and  $y$ , they can be neglected in a region sufficiently close to the SP, where the trajectory is governed by the *linear* matrix equation

$$\begin{pmatrix} dx/dt \\ dy/dt \end{pmatrix} \doteq \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = M \begin{pmatrix} x \\ y \end{pmatrix}$$

and  $\doteq$  indicates that the higher-order (nonlinear) terms have not been included. Sufficiently close to the SP, then, a trajectory evolves as

$$\begin{pmatrix} x \\ y \end{pmatrix} \doteq e^{\lambda t} \begin{pmatrix} x(0) \\ y(0) \end{pmatrix},$$

where  $\lambda$  is a solution of the determinantal equation

$$\det(M - \lambda I) = \det \begin{pmatrix} a - \lambda & b \\ c & d - \lambda \end{pmatrix} = \lambda^2 - (a + d)\lambda + ad - bc = 0.$$

As this is a quadratic equation, there are two solutions, which we can label  $\lambda_1$  and  $\lambda_2$ . In a curious mixture of German and English, it is customary to say that  $\lambda_1$  and  $\lambda_2$  are the *eigenvalues* of the matrix  $M$ , and the solutions of

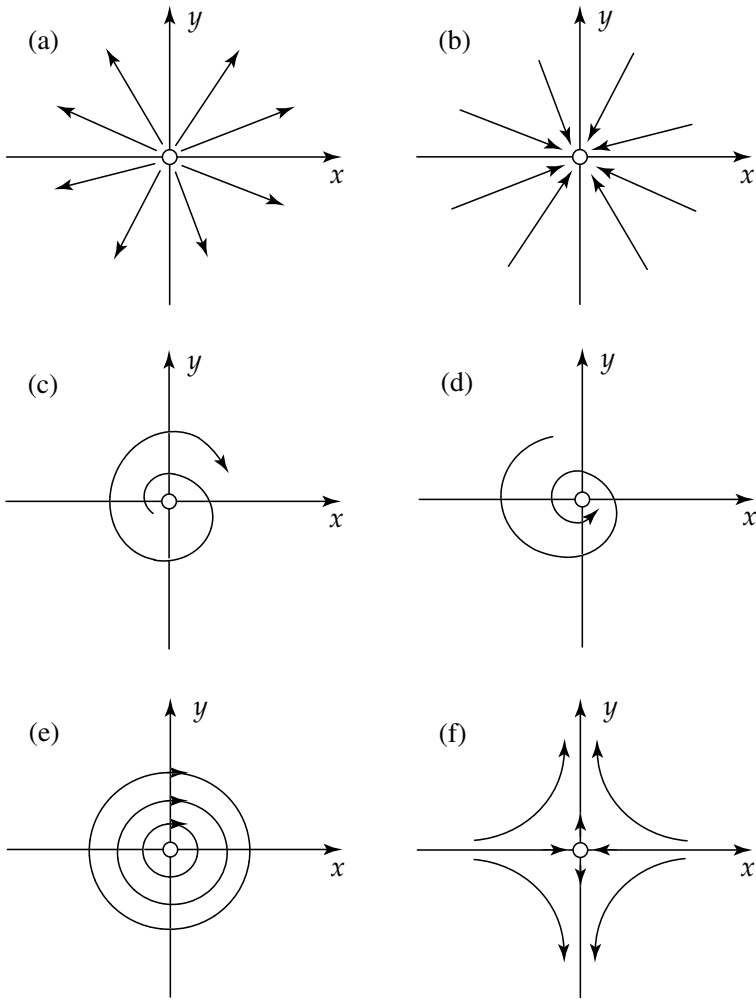
$$\begin{pmatrix} a - \lambda_1 & b \\ c & d - \lambda_1 \end{pmatrix} \begin{pmatrix} x_1 \\ y_1 \end{pmatrix} = 0, \quad \begin{pmatrix} a - \lambda_2 & b \\ c & d - \lambda_2 \end{pmatrix} \begin{pmatrix} x_2 \\ y_2 \end{pmatrix} = 0$$

are the corresponding *eigenvectors*. [The original English usage was to call  $\lambda_1$  and  $\lambda_2$  characteristic values and  $(x_1, y_1)$  and  $(x_2, y_2)$  the corresponding characteristic vectors but the bastard terms have carried the day.]

Let us now examine the generic behaviors of solution trajectories near singular points of a phase plane. Such a solution is of the general form

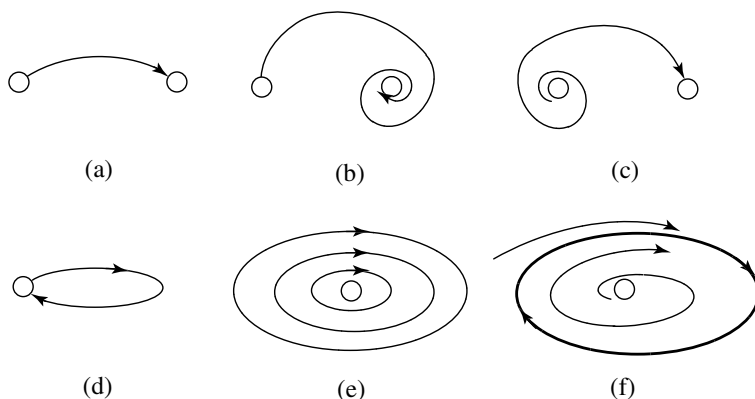
$$\begin{pmatrix} x \\ y \end{pmatrix} = A \begin{pmatrix} x_1 \\ y_1 \end{pmatrix} + B \begin{pmatrix} x_2 \\ y_2 \end{pmatrix},$$

where  $A$  and  $B$  are constants chosen so that  $x$  and  $y$  are real. (Thus if  $\lambda_1$  and  $\lambda_2$  are real then  $A$  and  $B$  are real, but if  $\lambda_1$  and  $\lambda_2$  are a complex-conjugate pair, then  $A$  and  $B$  are also a complex-conjugate pair.) The six possibilities are sketched in Fig. A.1, where axes have been scaled and the origin of the  $(x, y)$  plane has been moved to the SP for visual convenience.



**Fig. A.1.** The six generic singularities in the phase plane. (a) Outward node. (b) Inward node. (c) Outward spiral. (d) Inward spiral. (e) Center. (f) Saddle

- (a) Outward node. This is the case when both  $\lambda_1$  and  $\lambda_2$  are positive real numbers.
- (b) Inward node. In this case, both  $\lambda_1$  and  $\lambda_2$  are negative real numbers.
- (c) Outward spiral. Here  $\lambda_1$  and  $\lambda_2$  are a complex-conjugate pair with positive real parts.
- (d) Inward spiral. In this case,  $\lambda_1$  and  $\lambda_2$  are a complex-conjugate pair with negative real parts.
- (e) Center. In this final case, both  $\lambda_1$  and  $\lambda_2$  are purely imaginary numbers.



**Fig. A.2.** Finite nonlinear trajectories in the phase plane. (a), (b) and (c) show heteroclinic orbits. (d) A homoclinic orbit. (e) Nested cycles. (f) A limit cycle

(f) Saddle. In this case, both  $\lambda_1$  and  $\lambda_2$  are real, but one is positive and the other is negative.

As for global structures of nonlinear solutions on a phase plane, the requirement that trajectories cannot cross is a strong constraint, with the possibilities for finite nonlinear trajectories limited to those shown in Fig. A.2.

The first three examples in Figs. A.2a, b and c are *heteroclinic orbits* in which the phase point moves from one SP to another as time progresses from  $-\infty$  toward  $+\infty$ . Figure A.2d is an example of a *homoclinic orbit*, in which the phase point leaves from a saddle point at  $t = -\infty$  and returns to the same saddle as  $t \rightarrow +\infty$ . As discussed in Chap. 4, the examples of Figs. A.2a and d are particularly important for understanding the nature of impulse propagation on reaction-diffusion systems. The nested cycles of Fig. A.2e are topologically equivalent to the center in Fig. A.1e, but the example in Fig. A.2f is more interesting for technical applications. This is a *limit cycle*, in which periodic behavior is approached by trajectories of either larger or smaller amplitude, and the dynamic behavior corresponds to that of an electronic oscillator – a radio transmitter, for example. An inward node, and inward spiral, or a limit cycle will be embedded in a *basin of attraction* throughout which the same qualitative behavior obtains.

These examples capture the essential features of nonlinear dynamics on the phase plane, explaining why Newton and Euler were able to completely solve the two-body problem of planetary dynamics. Although there seem at first to be 12 dependent variables in this problem (the positions of both bodies in three-dimensional space and the corresponding components of their velocities), only the relative motions of the two bodies are relevant, reducing the number of dependent variables to 6. This number is further reduced to 2, because total energy is conserved along with angular momentum in three

directions; thus the two-body problem can be studied on a two-dimensional surface which is topologically equivalent to the phase plane.

If we increase the number of phase-space dimensions to 3, as in the Lorenz system of (2.1) and Fig. 2.1, the possible dynamical behaviors change dramatically because the prohibition on trajectories crossing on a surface no longer restricts the dynamics. From examination of the RHS functions of (2.1), it is evident that there is always one SP at

$$(x, y, z) = (0, 0, 0) .$$

For  $r > 1$ , there are two additional SPs at

$$(x, y, z) = \left( \pm\sqrt{b(r-1)}, \pm\sqrt{b(r-1)}, r-1 \right) ,$$

where it was noted in Chap. 2 that  $r$  represents a positive temperature difference driving the system. We can proceed as in the two-dimensional example by investigating the linear behaviors through analysis of the matrix

$$M = \begin{pmatrix} -\sigma & \sigma & 0 \\ r & -1 & 0 \\ 0 & 0 & -b \end{pmatrix} ,$$

which has only real eigenvalues:

$$\lambda_{1,2} = -(\sigma + 1)/2 \pm \sqrt{(\sigma - 1)^2/2 + r} , \quad \lambda_3 = -b ,$$

for  $r$  positive.

Thus there may be heteroclinic and homoclinic solution trajectories, as in Figs. A.2a and e, but knowing this tells us nothing about the possibility of finding the *strange attractor* shown in Fig. 2.1, which was discovered numerically by Lorenz [575]. Although the possibility of strange attractors had been known to Poincaré in the nineteenth century, teachers and students of physics and engineering remained largely unaware that such phenomena existed into the 1970s.

As we saw in Chap. 2, another interesting example of low-dimensional chaos is generated by the Hénon–Heiles Hamiltonian of (2.4), which was proposed in 1964 as a simple model of planetary dynamics. This energy functional is conserved under the dynamics, and it generates first-order ODEs in four dependent variables ( $x$ ,  $y$ ,  $p_x \equiv \dot{x}$ , and  $p_y \equiv \dot{y}$ ) through the *Hamiltonian equations* [364]:

$$\begin{aligned} \frac{dx}{dt} &= +\frac{\partial H}{\partial p_x} = p_x , \\ \frac{dy}{dt} &= +\frac{\partial H}{\partial p_y} = p_y , \\ \frac{d\dot{x}}{dt} &= -\frac{\partial H}{\partial x} = -\omega_1 x - 2\varepsilon xy , \\ \frac{d\dot{y}}{dt} &= -\frac{\partial H}{\partial y} = -\omega_2 y + \varepsilon(y^2 - x^2) , \end{aligned}$$

where  $p_x$  and  $p_y$  are *momenta* associated respectively with  $x$  and  $y$ . While these equations seem to define a four-dimensional phase space, conservation of energy requires solution trajectories to lie on surfaces defined by

$$H(p_x, p_y, x, y) = E ,$$

where the total energy  $E$  remains constant over time. Thus one of the dependent variables can always be expressed as a function of the other three, reducing the essential phase-space dimension to 3 as is indicated in Fig. 2.4.

The first two of the four Hamiltonian equations merely repeat the definitions of  $\dot{x}$  and  $\dot{y}$ , whereas the second two can be regarded as a pair of second order equations:

$$\frac{d^2x}{dt^2} + \omega_1 x = -2\varepsilon xy , \quad \frac{d^2y}{dt^2} + \omega_2 y = \varepsilon(y^2 - x^2) .$$

These two equations define oscillatory behavior on a torus as is sketched in Fig. 2.4a. For  $\varepsilon = 0$ , all trajectories lie on such tori, and for  $\varepsilon \ll 1$ , the KAM theorem tells us that most of them do. For  $\varepsilon \approx 1$ , chaotic regions begin to open up in the phase space, as is indicated in the Poincaré section of Fig. 2.4b.

Although the term “phase space” is now widely used in the above sense [399, 494], its etymological origin is unclear to many because “phase” has diverse meanings. In addition to the standard definition of “a distinct stage of development”, physical chemists speak of ice, liquid and vapor as the phases of water, astronomers observe the phases of Venus and the Moon, and engineers use phase to measure the degree to which a periodic function has progressed through a cycle – for example, a  $90^\circ$  phase change indicates passage through a quarter of a cycle. Perhaps this confusion is why electrical engineers in the United States coined the term “state space” in the early 1960s for a phase space, corresponding to the German term *Zustandsraum*.

The concept of a  $6n$ -dimensional space (with axes comprising the positions of  $n$  particles in ordinary three-dimensional space and their corresponding velocities or momenta) goes back to Joseph Lagrange and was developed by William Rowan Hamilton and Henri Poincaré (among others) in the latter decades of the nineteenth century, but Ludwig Boltzmann wrote only of the “differential equations of motion” in 1887 [107]. The term “phase” for a particular “configuration and velocity” of a set of interacting particles was employed by James Clerk Maxwell in 1879 (the year of his death) [620] and then picked up by Josiah Williard Gibbs [172]. Thus Gibbs wrote in the preface to his 1902 classic *Elementary Principles in Statistical Mechanics* that his studies were directed to [354]:

[...] the phases (or conditions with respect to configuration and velocity) which succeed one another in a given system in the course of time.

This definition comes close to “a distinct stage of development”, and the term “phase” may have been in Gibbs’s mind through his earlier analyses of thermodynamic states [351, 352] and of heterogeneous systems [353].

Maxwell’s terminology was originally coined to apply to the space of the  $6n$ -dimensional Hamiltonian equations governing the energy-conserving dynamics of  $n$  interacting particles, but present usage of the term “phase space” includes the solution space for any set of first-order nonlinear ODEs – for example the Lorenz system defined in (2.1).

## B Quantum Theory

The birthing of quantum theory (QT) is a checkered tale that began in 1901 with Max Planck's derivation of the black-body radiation law, which gives the relative intensity of light emitted from a hot object as a function of its wavelength. In this derivation, Planck was compelled – against his intuition – to propose that the energy of an atomic oscillator with frequency  $\omega$  is not continuously variable but restricted to discrete steps of size  $\hbar\omega$ , where

$$\hbar = 1.052 \times 10^{-34} \text{ joule seconds}$$

is a universal constant (now called *Planck's constant*) [763]. As one of the seminal papers of his 1905 “annus mirabilis”, Albert Einstein extended Planck's idea to explain the photoelectric effect (in which incident light causes electrons to be emitted from a metal if it has a sufficiently high frequency), by suggesting that light is particle-like, with a light particle (called a photon) of frequency  $\omega$  having an energy  $E = \hbar\omega$  [273].<sup>1</sup> In 1913, Niels Bohr proposed a model for the hydrogen atom in which a relatively light electron rotates about a heavier protonic nucleus in fixed orbits with angular momenta quantized in units of  $\hbar$ . Also light is emitted or absorbed at frequencies given by  $\Delta E/\hbar$ , where  $\Delta E$  is the difference in energies of two electronic states, allowing calculation of the absorption and emission spectra of hydrogen [102]. Louis de Broglie – in his 1924 doctoral thesis – proposed that atomic particles with momentum  $p$  should be characterized by a wavelength  $\lambda = 2\pi\hbar/p$ , as was soon confirmed at the Bell Telephone Laboratories by electron diffraction experiments of Clinton Davisson and Lester Germer [216].

Thus by the mid-1920s it was known that an atomic particle of energy  $E$  and momentum  $p$  is characterized by a frequency  $\omega$  and wavenumber  $k$  given by

$$\omega = \frac{2\pi}{T} = \frac{E}{\hbar} \quad \text{and} \quad k = \frac{2\pi}{\lambda} = \frac{p}{\hbar},$$

where  $T$  is a temporal period. In the autumn of 1925, Erwin Schrödinger began looking into this matter and soon concluded that there should exist a wave equation to describe the dynamics of an atomic particle. Although

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<sup>1</sup>It was for this idea that Einstein was awarded the Nobel Prize in 1918.



he seldom allowed work to interfere with vacations, Schrödinger devoted his 1925–26 winter holidays to this problem, thereby continuing “a twelve-month period of sustained creative activity that is without parallel in the history of science” [674]. He soon constructed the linear wave equation

$$i\hbar \frac{\partial \Psi(\mathbf{x}, t)}{\partial t} = V(\mathbf{x}, t)\Psi(\mathbf{x}, t) - \frac{\hbar^2}{2m} \nabla^2 \Psi(\mathbf{x}, t), \quad (\text{B.1})$$

in which  $\mathbf{x} \equiv x\mathbf{i} + y\mathbf{j} + z\mathbf{k}$  is the location of the particle in three dimensional space,  $m$  is its mass,  $V(\mathbf{x})$  is its potential energy as a function of position, and  $\nabla^2 \equiv \partial^2/\partial x^2 + \partial^2/\partial y^2 + \partial^2/\partial z^2$ .

Now known as the Schrödinger equation (SE), this is an important physical formulation because it gives the discrete energies of quantum states as eigenvalues of a linear PDE. Two results of this program, which Schrödinger immediately obtained, are as follows [909]. (i) Letting  $\mathbf{x} = x$  (i.e., assuming a one-dimensional problem) and setting  $V(x) = Kx^2/2$  (the potential energy of a linear spring) allows one to derive energy levels as

$$E_n = \hbar\omega(n + 1/2), \quad (\text{B.2})$$

which (except for the 1/2) is the relation that Planck was unhappily forced to assume in 1901 in his derivation of the black-body radiation formula. (ii) By writing the operator  $\nabla^2$  in spherical coordinates, the eigenvalues of (B.1) correspond exactly to the experimentally observed energy levels of atomic hydrogen. Furthermore, Schrödinger soon showed that his formulation is logically equivalent to a far more complicated matrix mechanics that had been proposed for QT by Werner Heisenberg in 1925 [416].

According to his biographer, Walter Moore, the first of a series of papers that Schrödinger wrote on this equation [850] was cited more than 100 000 times by 1960 and “has been universally recognized as one of the greatest achievements of twentieth-century physics” [674]. To help the reader appreciate the nature and implications of the Schrödinger equation, some brief comments on salient features of QT are listed.

### Solutions of the SE

- **Free Particle.** If  $V = 0$  in (B.1) – corresponding to a free classical particle – a general solution is

$$\Psi(\mathbf{x}, t) = \int F(\mathbf{k}) \exp[i(\mathbf{k} \cdot \mathbf{x} - \omega t)] d\mathbf{k} \quad (\text{B.3})$$

where  $\mathbf{k}$  is a three-dimensional wavenumber vector,  $F(\mathbf{k})$  is the spatial Fourier transform of the initial conditions (at  $t = 0$ ) and  $\omega = \hbar|\mathbf{k}|^2/2m$  is a corresponding *dispersion relation*.

- **Trapped Particle.** If  $V$  in (B.1) is a potential well (sufficiently negative in a localized region to trap a classical particle) and is independent of time, the time dependence in a component of the wave function appears merely as an exponential factor. Thus elementary solutions have the form  $\psi(\mathbf{x}) \exp(-iEt/\hbar)$ , where  $\psi(\mathbf{x})$  obeys the *eigenvalue equation*

$$\nabla^2 \psi(\mathbf{x}) + \frac{2m}{\hbar^2} [E - V(\mathbf{x})] \psi(\mathbf{x}) = 0, \quad (\text{B.4})$$

with bounded solutions for particular values of  $E$ . If one denotes these *energy eigenvalues* by  $E_n$  and the corresponding *eigenfunctions* of (B.4) by  $\psi_n(\mathbf{x})$ , a solution of (B.1) is

$$\Psi(\mathbf{x}, t) = \sum_n a_n \psi_n(\mathbf{x}) \exp(-iE_n t/\hbar), \quad (\text{B.5})$$

where the  $a_n$  are complex constants that can be chosen to fit some initial conditions (at  $t = 0$ , say). The solution of (B.1) can be written in this component form because it is a *linear* PDE, in contrast to the non-linear Schrödinger equation that was introduced in Chap. 3. It was by carrying through this calculation for a linear spring potential and for the  $1/r$  potential of electrostatic attraction between proton and electron in a hydrogen atom that Schrödinger obtained agreement with the Planck formula and the spectrum of atomic hydrogen, convincing him that (B.1) is physically relevant.

- **More General Cases.** Depending on the value of the energy ( $E$ ), solutions for a time-independent potential ( $V$ ) will be propagating (radiating) – as in (B.3) – in some regions of space and trapped in other regions – as in (B.5). If  $V$  depends weakly on time, perturbation theory can be used to calculate transitions from one bound state to another, corresponding to emission or absorption of radiation. If  $V$  depends strongly upon time, the classical motion may be chaotic, leading to a complicated quantum spectrum, which is described in Chap. 6.

### What Is $\Psi$ ?

Although (B.1) evidently has physical relevance, it was not immediately clear what aspect of reality is represented by the wave function  $\Psi$  because this quantity is a complex number (comprising both a real and an imaginary part). Is the real part of physical significance? Or should (B.1) be viewed as two coupled equations?

Following Schrödinger's observation that  $|\Psi|^2$  can be considered as the local density of electronic charge, Max Born soon proposed that this squared magnitude should be considered as the *probability density* of finding the particle with a certain region of space-time [113]. In other words, the probability

of finding the particle between  $x$  and  $x + dx$ ,  $y$  and  $y + dy$ ,  $z$  and  $z + dz$ , and  $t$  and  $t + dt$  is

$$\int_x^{x+dx} \int_y^{y+dy} \int_z^{z+dz} \int_t^{t+dt} |\Psi(x, y, z, t)|^2 dx dy dz dt, \quad (\text{B.6})$$

where  $|\Psi(x, y, z, t)|^2 = P(x, y, z, t)$  is the probability density in space-time. Although this interpretation of the quantum wave function as a probability amplitude is now universally accepted by physicists, there continue to be differences of opinion about what is meant by the term “probability”, as is discussed in Chap. 6.

### General Construction of a SE.

An intuitive understanding of the SE can be obtained by comparing it with the classical energy equation

$$\text{total energy} = \text{potential energy} + \text{kinetic energy},$$

where the LHS of (B.1) corresponds to the total energy and the RHS terms correspond to the classical potential and kinetic energies, respectively. More generally and compactly, a SE can be written as<sup>2</sup>

$$i\hbar\dot{\Psi} = H\Psi, \quad (\text{B.7})$$

where the dot indicates a time derivative and  $H$  is an *energy operator*. Thus (B.7) is constructed from the classical equation

$$E = H(p_x, x, p_y, y, p_z, z)$$

by replacing the energy  $E$  with the operator  $+i\hbar\partial/\partial t$ , the  $x$ -momentum  $p_x$  with  $-i\hbar\partial/\partial x$ , and so on.

As formulated by Schrödinger in 1926, the general aim of a quantum analysis is thus threefold: construct an energy operator from the classical Hamiltonian, find its eigenvalues and eigenfunctions, and write the general solution of the quantum problem as in (B.5). To indicate a sum over discrete eigenvalues (representing bound states) and integration over continuous eigenvalues (representing propagating states or radiation), Leonard Schiff has introduced the symbol [844]

$$\Psi = \mathbf{S} a_n(t) \psi_n \exp(-iE_n t/\hbar),$$

for a general solution of (B.7). Although the notation did not catch on with the physics community, the concept is important.

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<sup>2</sup>This equation appeared on the first-day postmark of the Austrian stamp honoring Schrödinger’s 100th anniversary in 1987 [674].

### Heisenberg's Uncertainty Principle.

As the structure of the general solution to a quantum problem is a generalized Fourier expansion (also called an eigenfunction expansion), the general solution shares the property that the product of the spreads of a variable and its transform are of order unity. Thus the products of minimum uncertainties in quantum variables are

$$\begin{aligned}\Delta p_x \times \Delta x &\approx \hbar, \\ \Delta p_y \times \Delta y &\approx \hbar, \\ \Delta p_z \times \Delta z &\approx \hbar, \\ \Delta E \times \Delta t &\approx \hbar.\end{aligned}\tag{B.8}$$

Heisenberg and Bohr claimed that these uncertainties establish a fundamental limit to what can be known about physical reality [416], whereas Einstein viewed it as an unsatisfactory aspect of QT [278].

### The Klein–Gordon (KG) Equation.

The SE of (B.1) is not invariant to a Lorentz transformation; thus it is not in accord with the SRT, which is to be expected because the separation of total energy into the sum of potential and kinetic components is not relativistically invariant. This is not a problem for the computation of interatomic levels and chemical binding energies because valence electrons are at rest. From (3.15), the general relation between energy and momentum of a moving particle is

$$E^2 = c^2 p^2 + m_0^2 c^4,$$

where  $m_0$  is the rest mass ( $m_0 = 8$  for a SG kink). Substituting  $E \rightarrow i\hbar\partial/\partial t$  and  $p \rightarrow i\hbar\partial/\partial x$  leads directly to the wave equation

$$\frac{\partial^2 \Psi}{\partial x^2} - \frac{1}{c^2} \frac{\partial^2 \Psi}{\partial t^2} = \left(\frac{m_0 c}{\hbar}\right)^2 \Psi,\tag{B.9}$$

which was derived independently by Oskar Klein and Walter Gordon (among several others, including Schrödinger) in 1926 as a relativistic wave equation with a rest mass [512]. The generalization of this linear PDE to the nonlinear SG equation was discussed in Sect. 3.4.

In the 1920s, and 1930s, KG was of minor interest as an electron model because it fails to represent spin. Currently, the KG equation is used for quantum models of spin-zero particles such as pions, and it can also be used to construct a quantum theory for a SG kink.

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