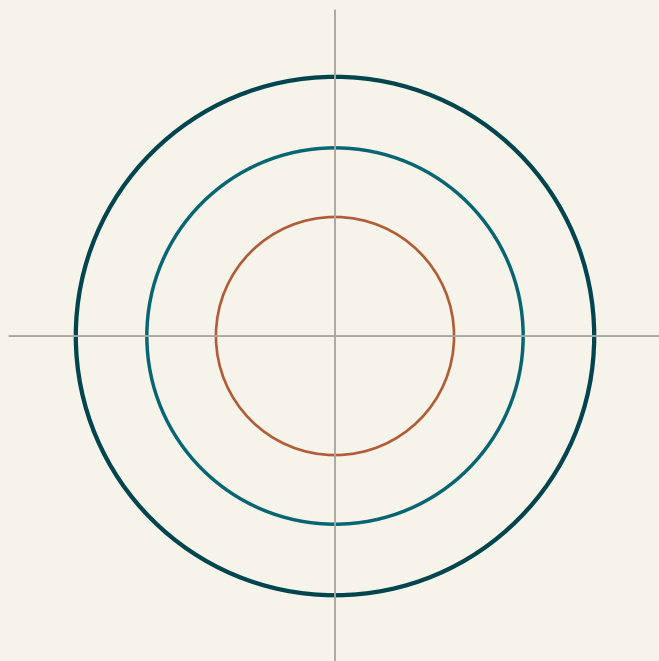


FOUNDATIONS OF QUANTUM MECHANICS

Quantum Motion Under Uncertainty

and the RFPA / AVPT Estimator



Ian Winfield Dansereau

Odisena

First Edition • 2026

Quantum Motion Under Uncertainty

*Foundations of Quantum Mechanics and the RFPA / AVPT
Estimator*

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Author: Ian Winfield Dansereau

Organization: Odisena

This book is a scientific and technical work. It presents established quantum mechanics and established estimation theory alongside the author's original RFPA / AVPT governed-estimator synthesis. Established results are attributed to their sources; the proposed governance architecture is clearly labelled as a proposal.

Every factual, web-derived claim in this book carries a numbered footnote marker in the body text, with the corresponding source and its full URL printed at the foot of the same page and consolidated in the Source Directory. All figures are original technical illustrations generated for this book; no copyrighted portraits, stock art, or external images are used.

The book does not assert that Heisenberg's uncertainty principle has been invalidated. It does not claim invention of quantum filtering, physicality-constrained estimation, quantum Kalman filtering, adaptive multi-model estimation, or state smoothing, all of which are acknowledged prior art. It makes no patentability or freedom-to-operate assertion; such questions require formal prior-art and legal review.

Set in Noto Serif (display) and Noto Sans (text).

Produced with a ReportLab pipeline and original vector figures.

A Note on What This Book Claims

This book has two jobs, and it keeps them visibly separate. The first is to be a faithful, accessible account of the parts of quantum mechanics that govern the motion of a quantum system and our attempts to observe it. The second is to present a specific engineering proposal: the RFPA / AVPT estimator, a governed architecture for predicting quantum motion under continuous measurement. The line between these two jobs is drawn deliberately and repeatedly, so that no reader mistakes an established theorem for a novel claim, or a proposal for a settled result.

Four categories, always labelled

Throughout, material falls into one of four categories. **Established quantum mechanics** is the textbook formalism: Hilbert spaces, the Born rule, unitary dynamics, uncertainty relations, open-system evolution. **Established estimation prior art** covers the Kalman filter, quantum filtering, physicality-constrained estimation, quantum Kalman filtering, adaptive multi-model estimation, and state smoothing. **The author's synthesis** is the way these strands are woven together for the problem of forecasting quantum motion. **The proposed governance layer** is the RFPA / AVPT contribution: evidence chains, validation gates, recovery, and tracked uncertainty ledgers wrapped around an established quantum filter.

PROPOSAL BOUNDARY

The estimator does not replace or weaken Heisenberg's principle. Its physicality gate *enforces* the Robertson–Schrödinger relation at every cycle. The novelty, if any, lies only in the specific integration and governance — not in the underlying quantum filter, the Kalman–Bucy reduction, physicality projection, or multi-model adaptation, all of which are prior art.

What the estimator does and does not output

Standard quantum mechanics does not supply an exact single future trajectory for a monitored particle. Neither does the estimator. What it produces is a conditional probability distribution over future position and momentum, together with a calibrated predictive envelope whose coverage can be tested against held-out data. This distinction is not a hedge; it is the honest content of the theory.

A pledge about uncertainty

The book never states that the uncertainty principle has been invalidated. The preparation relations of Kennard and Robertson are theorems of the formalism and remain so. Where the literature genuinely disagrees — for instance on measurement noise–disturbance relations — the disagreement is presented as an open question, not resolved by fiat.⁹

9. SEP — The Uncertainty Principle. <https://plato.stanford.edu/entries/qt-uncertainty/>

PREFACE

Preface

Physics earned its authority by predicting motion. Kepler's ellipses, Newton's laws, and the machinery of classical mechanics let us say where a planet or a projectile would be, and when. Quantum mechanics complicated that promise without breaking it. A quantum system still evolves under a precise equation, but what evolves is not a point in space; it is a state that yields probabilities. Motion under uncertainty is therefore not a failure of prediction. It is prediction of a different, richer kind: prediction of distributions, envelopes, and the odds of events.

I wrote this book because that richer kind of prediction has become an engineering discipline. In laboratories that levitate nanoparticles, cool mechanical oscillators, and read out superconducting qubits, physicists now watch quantum systems continuously and update their estimates in real time. The mathematics that makes this possible — quantum filtering, the stochastic master equation, the quantum Kalman–Bucy filter — is a direct descendant of the classical estimation theory that guides aircraft and spacecraft. The bridge between the two is one of the quiet triumphs of modern physics, and it deserves a clear telling.

The second half of the book is a proposal. Having taught the established machinery, I ask a concrete question: if we are going to trust a quantum estimator to forecast motion, how should we govern it? How do we keep its outputs physically valid, its uncertainty honestly accounted, and its evidence preserved so that a result can be reproduced and challenged? My answer is the RFPA / AVPT architecture — Recover, Field, Principal, Assumption; Attempt, Validate, Preserve, Track — an evidence-preserving loop I call the Infinity Engine. I present it as a proposal, with falsifiable hypotheses and acceptance criteria, not as a finished product.

Three readers were in my mind on every page. The general STEM reader should be able to follow the main narrative without a graduate background. The engineer or AI researcher will find sidebars that connect quantum estimation to filtering, covariance, and the discipline of validation. The graduate physicist will find the derivations, moment

equations, and definitions gathered in the appendices, where the mathematics is allowed to breathe.

I have tried to be scrupulous about attribution. Where a claim comes from the literature, it is cited on the page with a working link. Where the field is unsettled, I say so. Where the contribution is mine, I mark it as a proposal and bound it carefully. The goal is a book you can trust precisely because it tells you what to trust.

Ian Winfield Dansereau · Odisena · 2026

READER MAP

How to Read This Book

The book is layered so that three audiences can travel at different depths through the same terrain. You do not have to read everything to read profitably.

Three tracks

Track A — the main narrative. The running prose of every chapter is written for a general STEM reader. If you read only the body text and look at the figures, you will come away with an accurate mental model of quantum motion, measurement, and estimation, and a fair understanding of what the RFPA / AVPT proposal is for.

Track B — engineering notes. Sidebars marked *Engineering Note* connect the physics to the tools of estimation and machine learning: covariance matrices, recursive filters, validation gates, and provenance. Read these if you build systems or care about how the theory becomes code.

Track C — derivations and appendices. Boxes marked *Derivation* and the ten appendices carry the graduate-level mathematics: the Robertson–Schrödinger derivation, the Gaussian moment equations, the GKSL and stochastic-master-equation definitions, the Kalman–Bucy reduction, the quantum Fisher information and Cramér–Rao bound, the CHSH boundary, and the complete one-dimensional estimator.

The callout taxonomy

INTUITION

A plain-language picture of an idea, aimed at building the right mental model before the mathematics arrives.

ENGINEERING NOTE

A bridge to estimation and AI practice — how a physical idea maps onto filters, covariance, or governance.

DERIVATION

A compact but honest mathematical argument, self-contained enough to check, with fuller versions in the appendices.

PROPOSAL BOUNDARY

An explicit marker of where established science ends and the RFPA / AVPT proposal begins, including what is and is not claimed.

A note on notation and citations

Equations are typeset as display images so that symbols render crisply. Superscript numbers in the text point to sources listed at the foot of the same page, each with a full clickable URL; the same sources are gathered in the Source Directory at the back. Terms in the Glossary and symbols in the Symbols list are defined once and used consistently thereafter.

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1

Prologue: Motion Under Uncertainty

The thesis, the contract with the reader, and a pledge

Where will it be, and when? That single question has driven physics for four centuries. Quantum mechanics answers it — but in the language of probability, not certainty.

Classical mechanics made a clean promise. Give me the position and velocity of a particle now, together with the forces acting on it, and I will tell you where it will be at any later time. The promise was so successful that it shaped our idea of what an explanation is: to explain motion is to predict a trajectory. Quantum mechanics keeps the spirit of that promise while changing its terms. A quantum system evolves under an exact, deterministic equation, but the object that evolves is a *state* that encodes probabilities. Ask it where the particle will be, and it answers with a distribution.

This book is about that answer and how to make it useful. It is organized around one physical problem — the motion of a quantum system that we are continuously watching — and one engineering question: how should we build and govern a machine that forecasts such motion honestly? The first question is old and well settled in its foundations. The second is the reason this book is also a proposal.

A textbook and a proposal, kept apart

Most books are one thing. This one is deliberately two, and the seam between them is always visible. The textbook half explains established quantum mechanics: the Hilbert-space formalism, the Born rule, uncertainty relations, open-system dynamics, continuous measurement, and the classical-to-quantum bridge of filtering theory. The proposal half presents the RFPA / AVPT estimator, an architecture for governing a quantum filter so that its predictions stay physical, calibrated, and reproducible.

To keep the two honest, every substantial idea is placed in one of four categories: established quantum mechanics, established estimation prior art, the author's synthesis of those strands, and the proposed governance layer. When you reach a claim that is mine rather than the field's, a *Proposal Boundary* box will say so, and will state what is and is not being claimed.

PROPOSAL BOUNDARY

RFPA stands for Recover, Field, Principal, Assumption — the four steps that set up each estimation cycle. AVPT stands for Attempt, Validate, Preserve, Track — the four steps that execute it. Repeated indefinitely, the pair forms an evidence-preserving loop the book calls the Infinity Engine. These are the author's coinages; searches during the research for this book found no prior external use of the terms.

The pledge about Heisenberg

Popular accounts sometimes suggest that clever measurement or clever estimation can “beat” the uncertainty principle. This book makes no such claim, and it will be explicit about why. The preparation uncertainty relations of Kennard and Robertson are theorems of the quantum formalism: given the commutation relation between position and momentum, no state can have arbitrarily small spread in both at once.⁹

What is genuinely debated in the literature is a different and more subtle question about the noise and disturbance of a measurement, where results by Ozawa and by Busch, Lahti, and Werner refine — and disagree about — the measurement scenario. The book presents that debate as unsettled and never conflates it with the preparation relations. The estimator, far from defeating uncertainty, enforces the Robertson–Schrödinger bound as a hard constraint at every step.⁹

9. SEP — The Uncertainty Principle. <https://plato.stanford.edu/entries/qt-uncertainty/>

Two Distinct Ideas Often Conflated

Preparation uncertainty	Measurement disturbance
• Kennard (1927), Robertson (1929) • A theorem of the formalism • $\Delta_\psi A \Delta_\psi B \geq \frac{1}{2} \langle [A, B] \rangle$ • About states you can prepare • No reference to joint measurement • Established — not in dispute	• Heisenberg's microscope argument • Noise ϵ and disturbance η • Ozawa (2003): no positive lower bound • Busch–Lahti–Werner (2013): bound holds • About the act of measuring • A refinement still debated

The book never claims Heisenberg uncertainty is invalidated: the preparation relations remain theorems.

Figure 1.1. *Two ideas that are often conflated. Preparation uncertainty (left) is a theorem about which states can exist; measurement disturbance (right) is a distinct and still-debated question about the act of measuring.*⁹

What prediction means here

Because the state yields probabilities, the estimator's output is a probability distribution over future position and momentum, together with a calibrated predictive envelope. It does not claim to reveal a hidden exact trajectory, because standard quantum mechanics does not supply one. This is not a limitation to apologize for; it is the honest content of the theory, and it is exactly the kind of output that estimation engineering knows how to validate.

9. SEP — The Uncertainty Principle. <https://plato.stanford.edu/entries/qt-uncertainty/>

ENGINEERING NOTE

If you come from control or machine learning, the shift is familiar. A good forecaster does not emit a single number; it emits a distribution whose coverage you can check against held-out data. The quantum case simply adds a physical constraint — the uncertainty relation — that the distribution must respect.

The shape of the book

Part I builds the physics: history, the mathematical machinery, mixed states and measurement, uncertainty, and the Gaussian phase-space picture that makes the estimator tractable. Part II turns to watching and estimating: open systems and decoherence, continuous measurement, the filtering bridge from classical to quantum, the limits of estimation and the role of smoothing, the laboratories where this happens, and the interpretive questions that remain. Part III presents the RFPA / AVPT proposal in full, with falsifiable hypotheses and a roadmap. Ten appendices carry the derivations.

A reader who wants only the physics can stop at the end of Part II with a complete, accurate education in quantum motion and measurement. A reader who wants the proposal will find it built on that foundation, standing on the shoulders of established quantum filtering rather than in place of it.

2

From Quanta to Quantum Mechanics

How quanta, waves, and probability displaced classical determinism

In a single generation, physics traded the certainty of trajectories for the power of probability amplitudes — and gained a theory of unprecedented reach.

The quantum revolution did not arrive as a single insight but as a cascade of them, each forced by an experiment that classical physics could not explain. The story is worth telling carefully, both because it clarifies the concepts and because it shows how tentative and contested the early understanding was.

The first quantum: Planck, 1900

Max Planck introduced the quantum of energy in 1900 to explain the spectrum of black-body radiation, positing that energy is exchanged in

discrete amounts set by a new fundamental constant. The Nobel Committee later recognized him “in recognition of the services he rendered to the advancement of Physics by his discovery of energy quanta.” The constant that bears his name would become the measure of all quantum effects.¹

Five years later, Albert Einstein applied the same idea to light itself, explaining the photoelectric effect by treating radiation as composed of quanta. His 1921 Nobel Prize was awarded “for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect.” Light, it seemed, could behave as particles.²

Atoms and waves: Bohr and de Broglie

Ernest Rutherford's nuclear atom of 1911 left a puzzle: why did orbiting electrons not spiral into the nucleus? Niels Bohr answered in 1913 with a quantized model of hydrogen whose allowed orbits reproduced the observed Balmer spectral lines. Bohr's 1922 Nobel Prize honored “his services in the investigation of the structure of atoms and of the radiation emanating from them.”^{7,8}

In 1924 Louis de Broglie proposed a startling symmetry: if light waves could be particles, perhaps particles could be waves. His hypothesis that electrons have a wave nature, confirmed by diffraction experiments, earned the 1929 Nobel Prize “for his discovery of the wave nature of electrons.” The wave–particle duality was now unavoidable.³

1. NobelPrize.org — Planck facts. <https://www.nobelprize.org/prizes/physics/1918/planck/facts/>

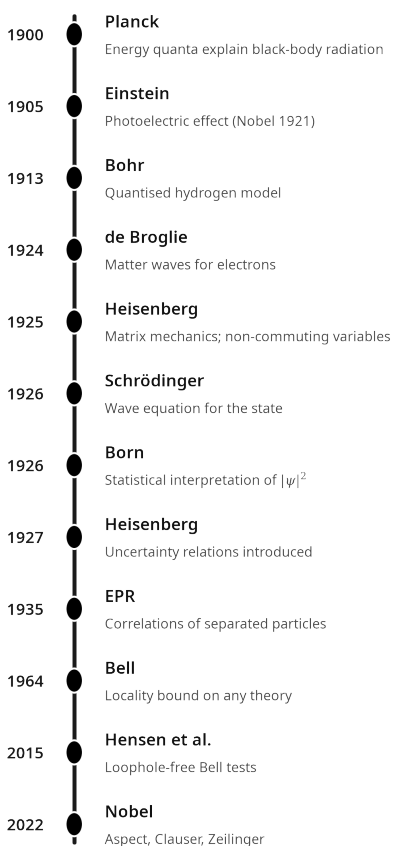
2. NobelPrize.org — Einstein facts. <https://www.nobelprize.org/prizes/physics/1921/einstein/facts/>

7. NobelPrize.org — Bohr facts. <https://www.nobelprize.org/prizes/physics/1922/bohr/facts/>

8. SEP — Copenhagen Interpretation. <https://plato.stanford.edu/entries/qm-copenhagen/>

3. NobelPrize.org — de Broglie facts. <https://www.nobelprize.org/prizes/physics/1929/broglie/facts/>

A Century of Quantum Milestones (1900–2022)



Prizes and results follow Nobel citations and the Stanford Encyclopedia of Philosophy.

Figure 2.1. A century of quantum milestones, from Planck's energy quanta to the 2022 Nobel Prize for experimental tests of Bell inequalities.^{1,10}

1. NobelPrize.org — Planck facts. <https://www.nobelprize.org/prizes/physics/1918/planck/facts/>

10. SEP — Bell's Theorem. <https://plato.stanford.edu/entries/bell-theorem/>

Two roads to mechanics: Heisenberg and Schrödinger

The decisive step came in 1925–1926, and it came twice. Werner Heisenberg built matrix mechanics, representing observable quantities by arrays of numbers that, crucially, do not commute: the order of measurement matters. His 1932 Nobel Prize was awarded “for the creation of quantum mechanics.” Almost simultaneously, Erwin Schrödinger wrote down a wave equation for a continuous state function, sharing the 1933 Prize with Paul Dirac “for the discovery of new productive forms of atomic theory.”^{4,5,8}

The two formalisms looked utterly different — discrete matrices versus continuous waves — yet they made identical predictions, and were soon shown to be equivalent. The equivalence is not a coincidence; both are representations of the same abstract structure, a point Chapter 3 makes precise.⁹

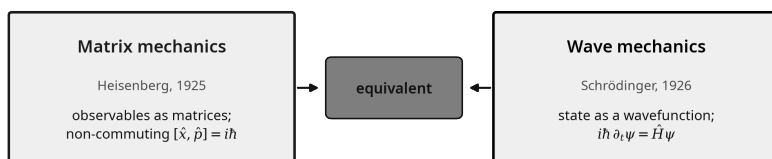
4. NobelPrize.org — Heisenberg facts. <https://www.nobelprize.org/prizes/physics/1932/heisenberg/facts/>

5. NobelPrize.org — Physics 1933. <https://www.nobelprize.org/prizes/physics/1933/summary/>

8. SEP — Copenhagen Interpretation. <https://plato.stanford.edu/entries/qm-copenhagen/>

9. SEP — The Uncertainty Principle. <https://plato.stanford.edu/entries/qt-uncertainty/>

Two Roads to the Same Quantum Mechanics



Born's statistical interpretation supplies the probabilities that connect either formalism to experiment.

Figure 2.2. *Matrix mechanics and wave mechanics are two representations of one theory. Born's statistical interpretation supplies the probabilities that connect either formalism to experiment.*^{4,6}

The meaning of the wave: Born, 1926

What was the wave function a wave *of*? Max Born supplied the answer that has endured: the squared magnitude of the wave function gives the probability of finding the particle. His 1954 Nobel Prize recognized “his fundamental research in quantum mechanics, especially for his statistical interpretation of the wavefunction.” With Born's rule, the theory acquired its characteristic feature — it predicts probabilities, not outcomes.^{6,11}

Heisenberg's 1927 paper introduced the uncertainty relations, and in the same year Bohr articulated complementarity at Como. Yet it is a historical misconception to speak of a single agreed “Copenhagen interpretation.” The term was coined by Heisenberg only in 1955, Bohr and Heisenberg never fully agreed, and Bohr in particular never described wave-function collapse or held that the observer causes outcomes.⁸

4. NobelPrize.org — Heisenberg facts. <https://www.nobelprize.org/prizes/physics/1932/heisenberg/facts/>

6. NobelPrize.org — Born facts. <https://www.nobelprize.org/prizes/physics/1954/born/facts/>

11. SEP — Quantum Mechanics. <https://plato.stanford.edu/entries/qm/>

8. SEP — Copenhagen Interpretation. <https://plato.stanford.edu/entries/qm-copenhagen/>

INTUITION

The early quantum theorists were not handing down commandments. They were arguing, revising, and often disagreeing. Reading the history this way inoculates against the false confidence that later textbooks can create — and it is good preparation for Chapter 12, where the interpretive debates are still alive.

From foundations to entanglement

The final act of the founding era pointed forward. In 1935 the Einstein–Podolsky–Rosen paper examined the correlations of two separated particles and argued that quantum mechanics must be incomplete. In 1964 John Bell turned that argument into a testable inequality, showing that no theory satisfying a locality condition can reproduce all quantum predictions. The experimental verdict, delivered over decades and honored with the 2022 Nobel Prize to Aspect, Clauser, and Zeilinger, favored quantum mechanics. Chapter 12 examines exactly what that verdict does, and does not, establish.¹⁰

10. SEP — Bell's Theorem. <https://plato.stanford.edu/entries/bell-theorem/>

3

The Mathematical Machinery

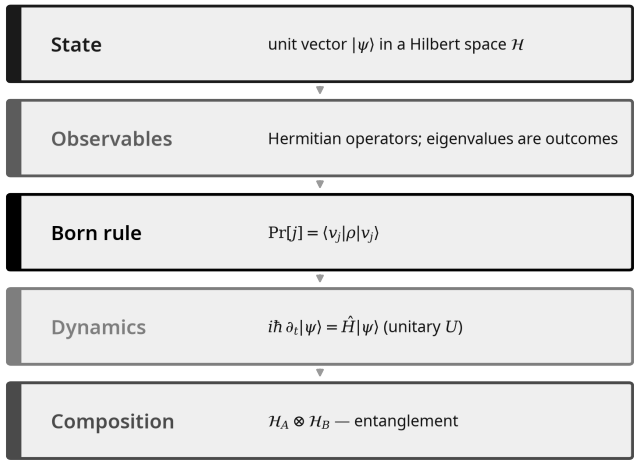
States, observables, the Born rule, and unitary dynamics

Strip away the interpretive debates and quantum mechanics is a compact set of postulates about vectors, operators, and probabilities. This chapter states them plainly.

The formalism of quantum mechanics can be summarized as a short stack of postulates. Each is precise, and together they suffice to make every prediction the theory offers. We present them in the order that a builder of estimators would want them: what a state is, what an observable is, how outcomes acquire probabilities, and how states evolve in time.¹¹

11. SEP — Quantum Mechanics. <https://plato.stanford.edu/entries/qm/>

The Postulate Stack of Quantum Mechanics



Each layer presupposes the one above; the bare postulates do not by themselves resolve the measurement problem.

Figure 3.1. *The postulate stack. Each layer presupposes the one above; the bare postulates do not by themselves resolve the measurement problem.*¹¹

States live in a Hilbert space

Every physical system is associated with a Hilbert space, a complex vector space equipped with an inner product. Every unit vector in that space represents a possible pure state of the system. We write such a state in Dirac notation as a ket, and its inner product with another as a bracket.¹¹

This single postulate already carries physics. Because states are vectors, they can be added: if two kets are possible states, so is their normalized sum. This is the superposition principle, and it is the origin of interference.

Observables are Hermitian operators

¹¹ SEP — Quantum Mechanics. <https://plato.stanford.edu/entries/qm/>

Physical quantities — position, momentum, energy, spin — are represented by Hermitian (self-adjoint) operators on the Hilbert space. The possible results of measuring a quantity are the eigenvalues of its operator, which for a Hermitian operator are guaranteed to be real. A system possesses a definite value of an observable precisely when its state is an eigenstate of that observable.¹¹

$$\hat{O} |b\rangle = a |b\rangle$$

The order in which operators are applied can matter. The failure of two observables to commute — the fact that applying them in different orders gives different results — is the algebraic seed of the uncertainty relations of Chapter 5. The canonical example is position and momentum.

$$[\hat{x}, \hat{p}] = \hat{x}\hat{p} - \hat{p}\hat{x} = i\hbar$$

The Born rule assigns probabilities

Measurement is where the formalism meets the world. When an observable is measured, the result is one of its eigenvalues, and the system is left in the corresponding eigenstate. Which eigenvalue occurs is a matter of probability, given by Born's rule. In the language of the density operator introduced in Chapter 4, the probability of the outcome associated with a basis state is the corresponding diagonal element.^{11,12}

11. SEP — Quantum Mechanics. <https://plato.stanford.edu/entries/qm/>

12. MIT 8.371 — Density Matrices & Decoherence. <https://web.mit.edu/8.371/www/resources/chap3.pdf>

$$\Pr[j] = \langle v_j | \rho | v_j \rangle$$

INTUITION

A pure state is like an arrow in a high-dimensional space. Measuring in a chosen basis is like asking which coordinate axis the arrow is closest to — but the answer is probabilistic, with the odds set by how much the arrow leans along each axis. The Born rule turns that geometric leaning into a number between zero and one.

Dynamics is unitary

Between measurements, a quantum state evolves deterministically. The Schrödinger equation determines the state at any later time through a time-evolution operator that is linear and unitary — it preserves inner products, and hence total probability. Nothing is lost or created; the evolution is perfectly reversible.¹¹

$$i\hbar \frac{d}{dt} |\psi(t)\rangle = \hat{H} |\psi(t)\rangle, \quad |\psi(t)\rangle = \hat{U}(t) |\psi(0)\rangle$$

The tension between deterministic unitary evolution and probabilistic measurement is the celebrated measurement problem. The bare postulates do not resolve it; they simply prescribe two different rules for two different situations. Chapters 7 and 12 return to this tension with the tools of decoherence and interpretation.¹¹

Composite systems and entanglement

When two systems are joined, their combined state lives in the tensor product of the individual Hilbert spaces. Crucially, not every state of the composite is a simple product of component states: there exist joint

¹¹ SEP — Quantum Mechanics. <https://plato.stanford.edu/entries/qm/>

states that cannot be factored. These are entangled states, and they encode correlations with no classical counterpart — the resource behind Bell's theorem and much of quantum technology.¹¹

$$\mathcal{H}_{AB} = \mathcal{H}_A \otimes \mathcal{H}_B$$

ENGINEERING NOTE

For an estimator, the useful reading of these postulates is operational. A state is a summary of everything you can predict; an observable is a question you can ask; the Born rule and the trace formula turn state-plus-question into a probability. Unitary evolution is a known, invertible propagation step — the quantum analogue of a linear dynamical model. Chapter 9 makes that analogy precise.

Why this suffices

Everything that follows — uncertainty, mixed states, open-system dynamics, continuous measurement, filtering — is built from these postulates plus the density-operator generalization of the next chapter. The appendices develop the consequences at graduate depth; the body text keeps to the ideas.

11. SEP — Quantum Mechanics. <https://plato.stanford.edu/entries/qm/>

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