

# The Spectral Theory of Observation: Modes, Collapse, and the Information Content of Reality

Not waves. Not particles. Modes that spread and get projected.

Tamas Nagy, Ph.D.

tnagyphd@gmail.com

Draft

## Abstract

We identify a single mathematical structure underlying seven apparently distinct physical frameworks: stochastic processes (Fokker–Planck), quantum mechanics (Schrödinger), statistical mechanics (transfer matrix), dynamical systems (Koopman), and information theory (rate-distortion). In each case, the system’s state is described by a density expanded in the eigenmodes of a linear generator:  $p = \sum c_k e^{\lambda_k t} \varphi_k$ . Evolution is mode-independent decay or oscillation. Observation is projection:  $c_k \rightarrow c_k \cdot \varphi_k(x_0)$ . “Wave–particle duality” becomes “many modes active (spread) vs few modes active (localized).” “Collapse” becomes “projection below the observer’s resolution threshold.” The Universal Spectral Representation Theorem (USRT) provides the quantitative backbone:  $N = \Theta(\log(1/\varepsilon)/\log \rho)$  modes suffice for  $\varepsilon$ -accuracy, independent of dimension, for any system with smooth dynamics. We demonstrate this unity across eight realizations: (1) portfolio risk measurement, (2) the three-body problem in celestial mechanics, (3) space debris collision probability, (4) machine learning model compression, (5) DeFi liquidation risk, (6) quantum decoherence prediction, (7) quantum measurement, and (8) mathematical knowledge growth — where the Fiedler vector of a theorem corpus’s Laplacian determines which theorem to prove next, making the framework self-referential: the spectral method observes its own corpus and chooses its next proof. The paper suggests that the “measurement problem” — the deepest open problem in physics — is not a problem of quantum mechanics specifically, but a universal property of spectral representations: observation is always projection, and the “collapse” is always the transition from  $N$  active modes to  $\sim 1$ .

---

## 1. The Observation

### 1.1 Five Systems, One Equation

Consider the following systems:

System	State	Generator	“Observation”
Stochastic process	Probability density $p(x, t)$	Fokker–Planck $\mathcal{L}_{\text{FP}}$	Measuring the position
Quantum particle	Wave function $\psi(x, t)$	Hamiltonian $H$	Detecting the particle
Thermal system	Boltzmann weight $\rho(\sigma)$	Transfer matrix $T$	Measuring temperature

System	State	Generator	“Observation”
Dynamical system	Observable $g(x_t)$	Koopman operator $\mathcal{K}$	Sampling the trajectory
ML model	Prediction function $f(x)$	Data covariance $\Sigma$	Testing on new data
DeFi position	Log-price density $p(X, t)$	Killed Fokker–Planck $M_{\text{killed}}$	Liquidation check
Open quantum system	Density matrix $\rho(t)$	Lindblad $\mathcal{L}$	Decoherence measurement
Theorem corpus	Knowledge state $p(d)$	Graph Laplacian $L$	Choosing next theorem

Each obeys the same evolution law:

$$\text{state}(t) = \sum_{k=0}^{N-1} c_k e^{\lambda_k t} \varphi_k \quad (1)$$

where  $\{\lambda_k, \varphi_k\}$  are the eigenvalues and eigenvectors of the generator. The differences:

	$\lambda_k$	$e^{\lambda_k t}$	Physics
Stochastic	Real, $\leq 0$	Exponential decay	Mixing, equilibration
Quantum	Imaginary, $iE_k/\hbar$	Oscillation	Interference, superposition
Thermal	Real, $\leq 0$	Exponential damping	Approach to equilibrium
Dynamical	Complex	Decay + oscillation	Attractors, chaos
ML	Real, $\geq 0$	Signal vs noise	Learning, generalization

## 1.2 What Is “Observation”?

In every framework, observation is the same operation:

$$c_k \xrightarrow{\text{observe at } x_0} c'_k = c_k \cdot \varphi_k(x_0) \quad (2)$$

The coefficients are updated by evaluating the eigenmodes at the observed point. This is **projection**: the infinite-dimensional state collapses to a point.

Framework	“Observation” in words	Equation (2) in that language
Stochastic	“We measured the satellite at position $x_0$ ”	$p \rightarrow \delta(x - x_0)$ , then re-expand
Quantum	“The detector clicked at position $x_0$ ”	$\psi \rightarrow \delta(x - x_0)$ , renormalize

Framework	“Observation” in words	Equation (2) in that language
Thermal	“We measured temperature $T$ ”	Fix macrostate, sum over microstates
Dynamical	“We sampled the trajectory at time $t_0$ ”	Koopman observable evaluated
ML	“We tested the model on input $x_0$ ”	$f(x_0) = \sum c_k \varphi_k(x_0)$

**In every case, observation is the SAME mathematical operation.** The “measurement problem” of quantum mechanics is the universal property of spectral representations: projection from many modes to one point.

## 2. The Five Realizations

### 2.1 Realization 1: Financial Risk

**Generator:** Fokker–Planck for correlated lognormal sum (the Spectral Fenton Distribution).

**State:**  $p(x) = \sum_{k=0}^{127} A_k \varphi_k(x)$  — 128 coefficients encoding the full loss distribution of an  $n$ -asset portfolio.

**Eigenvalues:**  $\lambda_k < 0$  — modes decay. Slow modes ( $|\lambda_k|$  small) represent large-scale risk (market regime). Fast modes ( $|\lambda_k|$  large) represent fine-grained risk (specific tail shape).

**Observation:** Computing VaR = finding  $x$  where  $F(x) = \alpha$ . This projects the 128-dimensional spectral state onto a single number.

**USRT bound:**  $N = 128$  suffices for  $\varepsilon < 10^{-14}$ , regardless of portfolio size  $n$ .

**Result:** 0.05% accuracy on OU process;  $16\times$  speedup on bank CVA (Nagy, 2026a–e).

### 2.2 Realization 2: The Three-Body Problem

**Generator:** Fokker–Planck for the stochastic CR3BP in the rotating frame.

**State:**  $p(x, v, t) = \sum c_k e^{\lambda_k t} \varphi_k(x, v)$  — the probability density over phase space.

**Eigenvalues:**  $\lambda_0 = 0$  (stationary),  $\lambda_1 < 0$  (mixing rate),  $\lambda_k \sim -k$  (Routh eigenfrequencies near L4/L5).

**Observation:** “Where is the test particle?” Projects the phase-space density to a position.

**Collapse:** Before observation, the particle is “everywhere” (density spread across modes). After observation, it is “here” (delta function). The spectral coefficients update via equation (2).

**Result:** 4.7% accuracy with 400 modes; spectral gap reveals mixing time; first passage via  $M_{\text{killed}}^{-1}$  (Nagy, 2026h).

### 2.3 Realization 3: Space Debris Collision

**Generator:** Fokker–Planck for miss-distance uncertainty with J2 + drag.

**State:**  $p(x, T_{\text{TCA}})$  — the density of miss distance at time of closest approach.

**Eigenvalues:** The spectral gap of the conjunction generator determines how fast uncertainty grows.

**Observation:** “Did they collide?” Projects the density onto  $\{|x| < R\}$ .

**The key result:** Gaussian “observation” (2D-Pc) **misses 2.4× the true probability** because it ignores excess kurtosis from J2. Spectral observation captures the full tail.

**Result:** 10,000 conjunctions in 13 seconds;  $\gamma = 2.37$  correction factor (Nagy, 2026i).

### 2.4 Realization 4: Machine Learning

**Generator:** Data covariance  $\Sigma = \mathbb{E}[xx^\top]$  of the input distribution.

**State:** The model’s prediction function  $f(x) = \sum_{k=0}^{K^*} c_k \varphi_k(x)$ , expanded in the eigenmodes of  $\Sigma$ .

**Eigenvalues:**  $\sigma_k^2$  (eigenvalues of the covariance). The model’s “knowledge” is  $\{c_k, \sigma_k^2\}$  — the spectral information state.

**Observation:** Testing on a new input  $x_0$  evaluates  $f(x_0) = \sum c_k \varphi_k(x_0)$ .

**Collapse:** The model’s knowledge (N-dimensional) projects to a single prediction (1-dimensional). Exactly equation (2).

**The duality result:** Bayesian and frequentist model selection both give  $K^* = \Theta(\log(n/\sigma^2)/\log \rho)$  — they agree on eigenvalues, disagree on  $\$ \$3$  modes near the boundary (Nagy, 2026j).

### 2.5 Realization 5: DeFi Liquidation Risk

**Generator:** Fokker–Planck for crypto log-price with state-dependent volatility (vol clustering  $\rightarrow$  excess kurtosis  $\kappa \approx 3\text{--}8$ ).

**State:**  $p(X, t)$  — the density of log-price  $X = \ln(S)$  at time  $t$ .

**Eigenvalues:**  $\lambda_0 = 0$  (stationary),  $|\lambda_1| =$  rate of price mean reversion, higher modes = tail dynamics.

**Observation:** “Has my position been liquidated?” = first passage:  $\tau = \inf\{t : X_t \leq \ln(L)\}$ .

**Collapse:** Before liquidation check: spread density (uncertain where price is). After checking: either “safe” (density conditioned on  $X > \ln(L)$ ) or “liquidated” (absorbed at barrier).

**The key result:** Gaussian models underestimate ETH liquidation probability by **2.3×** at 7-day horizon due to excess kurtosis. For stablecoins (USDT depeg risk):  $\gamma > 5\times$ . The expected liquidation time from a single matrix inverse:  $\mathbb{E}[\tau] = -\mathbf{1}^\top M_{\text{killed}}^{-1} A(0)$ . The  $\$40\text{B}$  LUNA/UST collapse was partly a failure of Gaussian risk models (Nagy, 2026k).

**Result:** 10,000 DeFi positions assessed in 0.6 seconds; optimal leverage from spectral gap.

## 2.6 Realization 6: Quantum Decoherence

**Generator:** Lindblad superoperator  $\mathcal{L}$  for an open quantum system (qubit + thermal bath).

**State:** Vectorized density matrix  $\text{vec}(\rho)$ . The Lindblad equation  $d\rho/dt = \mathcal{L}[\rho]$  is LINEAR — exactly our spectral framework.

**Eigenvalues:**  $\lambda_0 = 0$  (thermal equilibrium),  $|\lambda_1| = 1/T_1$  (energy relaxation rate),  $|\lambda_2| = 1/T_2$  (dephasing rate).

**Observation:** “Is the qubit still coherent?” = checking if the off-diagonal density matrix elements have decayed.

**The key result:** T1 and T2 predicted from Lindblad spectral gap with **0.00% error** on transmon qubit model. The T1(T) temperature curve is testable against IBM quantum hardware: sharp drop above 50 mK as thermal photons activate (Nagy, 2026l).

**Result:** The equation that prices derivatives and estimates collision probabilities also predicts when your qubit dies.

## 2.7 Realization 7: Quantum Measurement (Toy Model)

**Generator:** Hamiltonian  $H = -\frac{\hbar^2}{2m}\nabla^2 + V(x)$  for a particle in a potential well.

**State:**  $\psi(x, t) = \sum c_k e^{-iE_k t/\hbar} \varphi_k(x)$  — the wave function.

**Eigenvalues:**  $iE_k/\hbar$  — purely imaginary (no dissipation, unitary evolution). Energy levels.

**Observation:** Detecting the particle at  $x_0$ . The Born rule gives  $P(x_0) = |\psi(x_0)|^2 = |\sum c_k \varphi_k(x_0)|^2$ .

**Collapse:**  $\psi \rightarrow \delta(x - x_0)$  after detection. The coefficients update:  $c'_k = \varphi_k(x_0)$ .

**The spectral view of the measurement problem:** there is no “collapse.” There is **projection**. The  $N$  coefficients (each evolving independently) are evaluated at one point. The “before” state has  $N$  active modes (spread, “wave-like”). The “after” state has one dominant mode (localized, “particle-like”). The transition from  $N$  modes to  $\sim 1$  mode IS “collapse.” No mysticism required.

## 2.8 Realization 8: Mathematical Knowledge Growth

**Generator:** Graph Laplacian  $L = D - A$  of the theorem corpus (domains as nodes, imports as edges).

**State:**  $p = \sum c_k \varphi_k$  — the knowledge state expanded in the eigenvectors of  $L$ . The Fiedler vector ( $\varphi_2$ , eigenvector of  $\lambda_2$ ) partitions the corpus at its weakest link.

**Eigenvalues:**  $0 = \lambda_1 \leq \lambda_2 \leq \dots \leq \lambda_n$ . The algebraic connectivity  $\lambda_2$  measures how well-connected the knowledge is. For disconnected corpora,  $\lambda_2 = 0$  — the knowledge has “zero coherence.”

**Observation:** “Which theorem should we prove next?” This is the spectral projection problem: evaluate all candidate theorems by their Fiedler value  $(f_i - f_j)^2$ , then select the one that maximally improves  $\lambda_2$ .

**Collapse:** Before observation, the corpus is in a superposition of possible growth trajectories ( $N$  candidate bridges). After the choice, it collapses to a single theorem — and the Fiedler vector immediately updates.

## The spectral cycle in action:

GROW ( $e^{Mt} \rightarrow$  new theorem)  $\rightarrow$  MEASURE ( $\Delta\lambda_2$ )  $\rightarrow$  SELECT ( $\max(f_i - f_j)^2/c$ )  $\rightarrow$  GROW

This is identically the EVOLVE  $\rightarrow$  OBSERVE  $\rightarrow$  UPDATE cycle from Section 3.1, applied to mathematical knowledge. The “state” is the corpus graph, the “generator” is the Laplacian, and the “observation” is computing the Fiedler vector to decide where the knowledge is weakest.

**The USRT bound:**  $N_K = \Theta(\log(1/\varepsilon)/\log \rho_K)$  bridge theorems for  $\varepsilon$ -coverage, where  $\rho_K = e^{1/\lambda_2}$ .

**Empirical result** (Nagy, 2026m): a 6,011-theorem Lean corpus has  $\lambda_2 = 0$  (18 disconnected components). The Fiedler metric gives 0/10 overlap with the naive heuristic, correctly prioritizing island-to-mainland bridges over within-cluster densification. The greedy Fiedler strategy achieves  $(1 - 1/e)$  of optimal under submodularity.

**Why this matters:** the spectral observation framework describes not just physical systems but the growth of mathematical knowledge itself. The same equation governs portfolios, particles, debris, ML models, DeFi, decoherence, quantum measurement, and — most self-referentially — the theorem corpus that proves all of these. Observation-as-projection is universal. It applies even to the act of choosing what to prove next.

---

## 3. The Universal Structure

### 3.1 The Spectral Cycle

Every observation in every framework follows the same cycle:

EVOLVE ( $e^{Mt}$ )  $\rightarrow$  OBSERVE ( $\varphi_k(x_0)$ )  $\rightarrow$  UPDATE ( $c_k \rightarrow c'_k$ )  $\rightarrow$  EVOLVE  $\rightarrow$  ...

Phase	Mathematical operation	Physical meaning
EVOLVE	$c_k(t) = c_k(0) e^{\lambda_k t}$	Each mode evolves independently
OBSERVE	$c'_k = c_k \cdot \varphi_k(x_0)$	Evaluate all modes at observed point
UPDATE	Renormalize: $c'_k \rightarrow c'_k / \sqrt{\sum  c'_j ^2}$	Posterior = conditioned state

This is: - **Bayesian updating** in statistics (posterior  $\propto$  likelihood  $\times$  prior) - **Wave function collapse** in quantum mechanics ( $\psi \rightarrow \langle x_0 | \psi \rangle$ ) - **Kalman filtering** in engineering ( $\hat{x} \rightarrow \hat{x} + K(y - H\hat{x})$ ) - **Conditioning** in probability ( $p(x|y) = p(y|x)p(x)/p(y)$ )

All are projection in eigenspace. The name changes; the operation doesn't.

### 3.2 “Wave–Particle Duality” Is Mode Count

Description	Modes active	State	Classical name
All modes	$N$	$p = \sum c_k \varphi_k$ (spread)	“Wave”
One mode	1	$p \approx c_0 \varphi_0$ (localized)	“Particle”
Few modes	$K \ll N$	$p = \sum_{k=0}^K c_k \varphi_k$ (partially resolved)	“Measurement in progress”

There is no duality. There is a CONTINUUM from  $N$  modes (fully spread) to 1 mode (fully localized). Observation moves you along this continuum. Evolution moves you back (modes spread again).

### 3.3 The USRT as Information Budget

The USRT says: for any system with smoothness  $\rho > 1$ , the complete state requires

$$N = \Theta\left(\frac{\log(1/\varepsilon)}{\log \rho}\right)$$

modes. This is the **information budget** of reality:

- $\varepsilon = 10^{-3}$ : you need  $\sim 10$  modes (rough picture)
- $\varepsilon = 10^{-6}$ : you need  $\sim 20$  modes (detailed)
- $\varepsilon = 10^{-14}$ : you need  $\sim 47$  modes (machine precision)
- $\varepsilon = 0$  (perfect knowledge):  $N \rightarrow \infty$  — **impossible**

**Perfect knowledge of any system requires infinite information.** This is not a limitation of measurement instruments — it is a property of spectral representations. The Heisenberg uncertainty principle, the Cramér–Rao bound, the Shannon channel capacity, and the USRT are all manifestations of the same truth: **observation with finite resources ( $N$  modes) cannot fully determine a continuous state.**

## 4. The Measurement Problem, Spectrally

### 4.1 What the Measurement Problem Actually Asks

The quantum measurement problem asks: when and how does the wave function “collapse” from a superposition  $\psi = \sum c_k \varphi_k$  to a definite state  $\varphi_j$ ?

### 4.2 The Spectral Answer

It doesn’t “collapse.” It is **projected**. The observer’s finite resolution  $\varepsilon$  determines how many modes are resolvable:

$$K^*(\varepsilon) = \left\lceil \frac{\log(1/\varepsilon)}{\log \rho} \right\rceil$$

Modes  $k > K^*$  are below the observation threshold. They still exist — they are simply invisible to this observer.

**“Collapse” = the transition from  $K^*$  resolved modes to  $K^* = 1$  (a single outcome).**

This is observer-dependent (different observers with different  $\varepsilon$  see different  $K^*$ ), but the state  $p = \sum c_k \varphi_k$  is observer-independent. The coefficients  $c_k$  are the reality. The number of modes an observer can see ( $K^*$ ) is their window into that reality.

### 4.3 Why This Isn’t Decoherence

Decoherence theory (Zurek, 2003) explains the *appearance* of collapse via interaction with the environment: off-diagonal density matrix elements decay, making the state look classical. Our spectral view is compatible but different:

- Decoherence: environment causes  $\lambda_k$  to acquire a real (negative) part  $\rightarrow$  modes decay  $\rightarrow$  looks classical
- Spectral: the observer’s resolution  $\varepsilon$  determines which modes are visible, regardless of decoherence

Decoherence explains WHY modes decay. The USRT explains HOW MANY modes remain relevant after decay.

### 4.4 What This Predicts

If the spectral theory of observation is correct, then:

1. **Every measurement apparatus has a spectral resolution  $\varepsilon$** , and the number of distinguishable outcomes is  $K^*(\varepsilon)$ .
2. **The “basis problem”** (why does collapse happen in the position basis rather than the momentum basis?) has a spectral answer: the basis is determined by the eigenvectors of the system-apparatus interaction Hamiltonian.
3. **The Born rule** ( $P = |c_k|^2$ ) is the unique probability assignment consistent with the USRT’s orthogonality of modes.

## 5. The Unified Table

The complete spectral dictionary:

Concept	Stochastic	Quantum	Statistical mech.	Dynamical sys.	ML
State	$p(x)$	$\psi(x)$	$\rho(\sigma)$	$g(x)$	$f(x)$
Generator	$\mathcal{L}_{FP}$	$H$	$T$	$\mathcal{K}$	$\Sigma$
Eigenvalues	Decay rates	Energies	Boltzmann	Lyapunov	Signal power
“Spread”	Diffusion	Superposition	Fluctuation	Sensitivity	Uncertainty
“Observe”	Measure $x$	Detect particle	Measure $T$	Sample	Test
“Collapse”	Condition	Born rule	Fix macro	Evaluate	Predict

Concept	Stochastic	Quantum	Statistical mech.	Dynamical sys.	ML
USRT	$N \sim 130$	$N \sim E/\Delta E$	$N \sim k_B T/\Delta E$	$N \sim \lambda T$	$N \sim K^*$

---

## 6. Limitations

1. **The quantum case is imaginary eigenvalues.** In QM,  $\lambda_k = iE_k/\hbar$  — modes oscillate, they don't decay. There is no natural “loss of resolution” as in the stochastic case. The measurement problem IS harder in QM because information is never lost (unitary evolution). Our spectral view reframes the problem but does not solve it.
2. **The Born rule is not derived.** We observe that  $P = |c_k|^2$  is consistent with spectral orthogonality, but we do not derive it from first principles. Gleason's theorem (1957) does this under certain axioms; whether the USRT adds to this is an open question.
3. **Nonlinear systems.** The spectral framework assumes a linear generator. Nonlinear dynamics (turbulence, general relativity) require Koopman lifting or mean-field approximations. The USRT applies to the lifted system but the lifting may introduce artificial dimensions.
4. **This is a framework, not a theory.** We do not make testable predictions that distinguish this view from standard QM + decoherence. The value is conceptual (unification) and practical (computational).

---

## 7. Conclusion

Eight frameworks. One equation. One observation operation. One convergence bound.

The spectral decomposition of a system's generator is not merely a mathematical tool — it is the natural representation of physical reality. Evolution is mode-independent. Observation is projection. “Collapse” is resolution-limited projection. The USRT provides the information budget:  $N = \Theta(\log(1/\varepsilon)/\log \rho)$  modes, independent of dimension.

The measurement problem, viewed spectrally, is not why observation produces definite outcomes. It is why we, as finite-resolution observers ( $K^* < \infty$ ), perceive a continuous world as discrete events. The answer: because the USRT forces  $K^*$  to be finite.

$$p = \sum_{k=0}^{N-1} c_k e^{\lambda_k t} \varphi_k$$

Not waves. Not particles. Not even theorems. Modes that spread and get projected — in portfolio risk, in quantum mechanics, and in the mathematical corpus that proves them all equivalent.

---

*During the preparation of this work the author used large language models in order to assist with manuscript drafting, literature search, and coding assistance. After using these tools, the author reviewed and edited the content as needed and takes full responsibility for the content of the published article.*

---

## References

- Bell, J. S (1964). On the Einstein Podolsky Rosen Paradox. *Physics*, 1(3).
- Gleason, A. M (1957). Measures on the closed subspaces of a Hilbert space. *J. Math. Mech.*
- Koopman, B. O (1931). Hamiltonian systems and transformations in Hilbert space. *Proceedings of the National Academy of Sciences*, 17(5).
- Nagy, T. (2026). Lean 4 Formal Verification of the Spectral Fenton Distribution and Related Financial Mathematics. *Working paper*.
- Nagy, T. (2026). The Quantum Spectral Representation Theorem: What Can and Cannot Be Compressed. *Working paper*.
- Nagy, T. (2026). The Spectral Tensor Representation of Stochastic Processes. *Working paper*.
- Nagy, T. (2026). The Three-Body Problem Solved Distributionally: Spectral Fokker-Planck for the Circular Restricted Three-Body Problem. *Working paper*.
- Nagy, T. (2026). The Spectral Information State. *Working paper*.
- Nagy, T. (2026). The Duality of Bayesian and Frequentist Statistics. *Working paper*.
- Shannon, C.E (1948). A Mathematical Theory of Communication. *Shannon, C.E.*, 27(3). DOI: 10.1109/9780470544242.ch1
- Zurek, W. H (2003). Decoherence, einselection, and the quantum origins of the classical. *Reviews of Modern Physics*. DOI: 10.1103/revmodphys.75.715
- Nagy, T. (2026). The Knowledge Artifact and Knowledge Algebra of Machine Learning Models. *Zenodo*. DOI: 10.5281/zenodo.18910387
- Nagy, T. (2026). The Spectral Theory of Knowledge: Optimal Growth of a Machine-Verified Mathematical Corpus. *Working paper*.
- Fiedler, M (1973). Algebraic connectivity of graphs. *Czechoslovak Mathematical Journal*, 23(2), 298-305.
- Ghosh, A. and S. Boyd (2006). Growing well-connected graphs. *IEEE CDC*.