Physics-and-Programming: A Compact Equation Companion

Abstract

This document provides a research-note style companion to the visualizations in the `QuantumStuff` folder. Each section summarizes the physical idea, gives the governing equations used in the code, and adds brief interpretive remarks or examples. The goal is clarity rather than completeness; the formulas are faithful to the scripts and are intended for intuition-building and qualitative analysis.

Notation and Conventions

We use x, y for spatial coordinates, t for time, $\vec{r}$ for position, and $\vec{v}$ for velocity. Dots indicate time derivatives, e.g. $\dot{x} = dx/dt$. Constants are chosen in the scripts for visual clarity; many figures use normalized units where $\hbar = 1$, $c = 1$, or $m = 1$. Unless otherwise stated, equations are not claimed to be high-precision physical models.

QuantumStuff/4th_dimension_viz.py (Gravitational Lensing Toy Sheet)

This visualization treats curved spacetime as a 2D surface with a central potential well and traces a bent light path. The warping function is normalized to keep the edges near zero while deepening near the center. The light ray is a base line plus a Gaussian bend term.

$$r = \sqrt{x^2 + y^2}$$

$$z_0 = -\frac{W}{\sqrt{r^2 + s^2}}, \quad z = -W \cdot \frac{z_0 - z_{0,\min}}{0 - z_{0,\min}}$$

$$x_{\text{base}}(t) = x_s + (x_e - x_s)t, \quad y_{\text{base}}(t) = y_s + (y_e - y_s)t$$

$$y_{\text{path}} = y_{\text{base}} - 1.3\, e^{-(x_{\text{base}})^2/(2\cdot 1.1^2)}$$

Example: increasing W deepens the well and makes curvature more dramatic, even though the ray is still a scripted path.

QuantumStuff/atomic_bomb_viz.py (Stylized Chain Reaction)

This is a non-physical, artistic particle animation. Motion is simple advection with wall bounces; "splitting" triggers are randomized collisions.

$$x_{t+1} = x_t + v_x, \quad y_{t+1} = y_t + v_y$$

$$v_x \to -v_x \text{ if } x \notin [X_{\min}, X_{\max}], \quad v_y \to -v_y \text{ if } y \notin [Y_{\min}, Y_{\max}]$$

$$r = U^{0.6}(0.7R), \quad dx = r\cos\theta, \quad dy = r\sin\theta$$

$$\text{hit if } (x - x_n)^2 + (y - y_n)^2 \le (R + 0.12)^2$$

QuantumStuff/atom_viz.py (Electron Cloud Toy)

Electrons move on noisy circular paths to convey "cloud-like" behavior. The nucleus is a small random cluster.

$$r = RU^{1/3}, \quad x = r\cos\theta, \quad y = r\sin\theta$$
$$\theta_{t+1} = \theta_t + \omega \cdot 0.03, \quad r(t) = r_0 + A\sin\phi$$
$$x = r\cos\theta, \quad y = r\sin\theta$$

Example: increasing jitter amplitude A makes the electron cloud appear more diffuse.

QuantumStuff/blackhole_viz.py (Cinematic Black Hole)

A synthetic field combines a lensed starfield, a photon ring, and accretion disk textures. The equations are stylized but capture qualitative features like beaming and falloff.

$$\alpha = \frac{L}{r^2}, \quad (x', y') = (x, y) + \alpha\left(\frac{x}{r}, \frac{y}{r}\right)$$
$$\text{disk radial} = \exp\left(-\frac{(R - R_d)^2}{W^2}\right)$$
$$\text{doppler} = 0.32 + 0.68 \cdot \frac{1 + \cos(\theta - \Omega t)}{2}$$
$$\text{spiral} = 0.5 + 0.5\cos\left(m(\theta - 1.4\Omega t)\right)$$
$$\text{hole falloff} = 1 - \exp\left[-\left(\frac{R}{R_s}\right)^3\right]$$

QuantumStuff/collision_bh_viz.py (Binary Merger Toy)

Two softened potentials orbit inward and merge. A sinusoidal radial ripple imitates gravitational waves.

$$\Phi(x, y) = \frac{1}{\sqrt{(x - x_c)^2 + (y - y_c)^2 + \epsilon^2}}$$
$$x_{1,2} = \mp\frac{s}{2}\cos\phi, \quad y_{1,2} = \mp\frac{s}{2}\sin\phi$$
$$\text{ring} = \exp\left(-\frac{(r - r_0)^2}{w^2}\right)$$
$$\text{GW ripple} = e^{-\gamma|R - r_0|}\sin(k(R - r_0))$$

QuantumStuff/dark_matter_viz.py (Halo Intuition)

A smooth halo profile extends beyond the luminous disk to suggest flat rotation curves. Tracers follow roughly constant angular speeds.

$$I(r) = \frac{1}{1 + (r/r_c)^2} + \frac{1.8}{1 + (r/R_h)^3}$$
$$\theta_{t+1} = \theta_t + \omega, \quad x = r\cos\theta, \quad y = r\sin\theta$$
$$(dx, dy) = \eta\frac{(x, y)}{r^2}$$

QuantumStuff/doppler_eff_viz.py (Doppler Effect)

Wavefronts are emitted periodically from a moving source. In front of the source, crests are compressed; behind, they spread out.

$$x_s(t) = x_0 + v_s t$$

$$r_{\text{out}} = c(t - t_0), \quad r_{\text{in}} = R_0 - c(t - t_0)$$

QuantumStuff/double_pendulum_chaos_viz.py (Chaotic Dynamics)

The standard double-pendulum equations are integrated with RK4. A tiny initial angle difference leads to exponential divergence.

$$x_1 = L_1 \sin\theta_1, \quad y_1 = -L_1 \cos\theta_1$$

$$x_2 = x_1 + L_2 \sin\theta_2, \quad y_2 = y_1 - L_2 \cos\theta_2$$

$$\ddot{\theta}_1 = \frac{M_2 L_1 \omega_1^2 \sin\Delta \cos\Delta + M_2 g \sin\theta_2 \cos\Delta + M_2 L_2 \omega_2^2 \sin\Delta - (M_1 + M_2) g \sin\theta_1}{(M_1 + M_2) L_1 - M_2 L_1 \cos^2\Delta}$$

$$\ddot{\theta}_2 = \frac{-M_2 L_2 \omega_2^2 \sin\Delta \cos\Delta + (M_1 + M_2)(g \sin\theta_1 \cos\Delta - L_1 \omega_1^2 \sin\Delta - g \sin\theta_2)}{(L_2/L_1)((M_1 + M_2) L_1 - M_2 L_1 \cos^2\Delta)}$$

QuantumStuff/double_slit_viz.py (Particle Double Slit)

Particles are launched, checked against slit openings, and if transmitted are spread by a Gaussian "diffraction" jitter.

$$y_b = y_0 + \mathcal{N}(0, \sigma_b)$$

$$\text{pass if } |y_b - \pm y_s| \le \frac{h}{2}$$

$$y_{\text{screen}} = y_b + \mathcal{N}(0, \sigma_d)$$

QuantumStuff/electric charges interaction.py (Coulomb Field)

The electric field is computed from two charges and visualized with streamlines and quivers. Force vectors are shown for intuition.

$$\vec{E}(\vec{r}) = kq \frac{\vec{r} - \vec{r}_q}{(|\vec{r} - \vec{r}_q|^2 + \epsilon^2)^{3/2}}$$

$$\vec{F}_{12} = k \frac{q_1 q_2}{r^2} \hat{r}, \quad \vec{F}_{21} = -\vec{F}_{12}$$

QuantumStuff/electric field.py (Single Charge Field)

A softened point-charge field is used to avoid singularity at the origin.

$$\vec{E}(\vec{r}) = kq \frac{\vec{r}}{(r^2 + \epsilon^2)^{3/2}}$$

QuantumStuff/enthropy_viz.py (Shannon Entropy)

Particles diffuse randomly in a box while the Shannon entropy of the 2D histogram rises.

$$\vec{x}_{t+1} = \vec{x}_t + \mathcal{N}(0, \sigma^2)$$

$$H = -\sum_i p_i \log_2 p_i$$

QuantumStuff/fission_fusion_viz.py (Stylized Nuclear Processes)

This is a safe, non-physical visualization contrasting fission-like and fusion-like motions.

$$x_{t+1} = x_t + v_x, \quad y_{t+1} = y_t + v_y, \quad \vec{v} \to 0.97\vec{v}$$

$$\text{split if } (x - x_n)^2 + (y - y_n)^2 \le (R + \delta)^2$$

$$\text{fusion if } (x_a - x_b)^2 + (y_a - y_b)^2 \le d_f^2 \text{ and } U < p_f$$

QuantumStuff/fluid_vortex_viz.py (Kármán Vortex Street Toy)

A synthetic velocity field mimics flow past a cylinder with alternating wake shedding.

$$\vec{u} = \vec{u}_{\text{base}} + \vec{u}_{\text{deflect}} + \vec{u}_{\text{wake}}$$

$$\text{deflect} = \frac{R_c^2}{r^2}, \quad u_d = -1.2(xy)\,\text{deflect}$$

$$v_d = 0.6\left(1 - \frac{2y^2}{r^2}\right)\text{deflect}$$

$$u_{\text{wake}} = 0.25e^{-0.6(x-R_c)}\sin(\pi y), \quad v_{\text{wake}} = 0.6e^{-0.6(x-R_c)}\sin\left(2\pi(ft - 0.35x)\right)$$

QuantumStuff/gravitational_lensing_viz.py (Point-Mass Lens)

The standard lens equation is used to remap a background texture as the Einstein radius varies.

$$\boldsymbol{\beta} = \boldsymbol{\theta} - \theta_E^2 \frac{\boldsymbol{\theta}}{|\boldsymbol{\theta}|^2}$$

QuantumStuff/hawkin's_rad_viz.py (Hawking Radiation Toy)

A bright halo and expanding rings suggest radiation escaping the horizon.

$$\text{glow} = \exp\left(-\frac{(R - R_h)^2}{w^2}\right)$$

$$R_{\text{wave}} = R_h + v(t - t_0), \quad \text{ring} = \exp\left(-\frac{(R - R_{\text{wave}})^2}{\sigma^2}\right)$$

QuantumStuff/hawking_particles_escape_viz.py (Particle Escape Toy)

Discrete particles arc outward with mild angular drift.

$$r = R_h + v(t - t_0)$$
$$\theta = \theta_0 + s\kappa \left(1 - e^{-\beta(r-R_h)}\right) + 0.08 \sin(\omega t + \phi)$$
$$x = r\cos\theta, \quad y = r\sin\theta$$

QuantumStuff/hydrogen_bomb_viz.py (Stylized Fusion)

A decorative "fusion" animation with proximity checks and luminous flashes.

$$x_{t+1} = x_t + v_x, \quad y_{t+1} = y_t + v_y$$
$$\vec{v} \leftarrow \vec{v} + 0.02 \frac{-\vec{r}}{r} \text{ if } r > r_{\max}$$
$$\text{fusion if } (x_i - x_j)^2 + (y_i - y_j)^2 \le d_f^2 \text{ and } U < p_f$$

QuantumStuff/interferometer_gw_viz.py (GW Interferometer)

A Michelson-like setup shows arm-length modulation and the resulting phase shift.

$$h(t) = A\sin(2\pi f t)$$
$$L_x = L(1 + \tfrac{1}{2}h), \quad L_y = L(1 - \tfrac{1}{2}h)$$
$$\Delta\phi = \frac{4\pi}{\lambda}(L_x - L_y)$$
$$I = \frac{1}{2}\left(1 + \cos\Delta\phi\right)$$

QuantumStuff/maxwell_wave_viz.py (Plane EM Wave)

A 1D plane wave satisfies Maxwell's equations in vacuum; E and B are in phase and orthogonal.

$$E_y(x,t) = E_0 \sin(kx - \omega t)$$
$$B_z(x,t) = \frac{E_0}{c}\sin(kx - \omega t), \quad \omega = ck$$

QuantumStuff/newton_laws_viz.py (Newton's Laws)

The animation shows inertia, $F = ma$, and equal-and-opposite impulses in three panels.

$$x(t) = x_0 + vt \quad (\Sigma F = 0)$$
$$a = \frac{F}{m}, \quad v_{t+1} = v_t + a\Delta t, \quad x_{t+1} = x_t + v_{t+1}\Delta t$$
$$\vec{J}_1 = -\vec{J}_2$$

QuantumStuff/particle_acc_viz.py (Circular Accelerator Toy)

Particles move on a ring; collision events are triggered near a fixed interaction point.

$$\theta_{t+1} = \theta_t + \omega, \quad x = x_0 + r\cos\theta, \quad y = y_0 + r\sin\theta$$

$$\text{collision if } |\Delta\theta| < \theta_{\text{window}}$$

QuantumStuff/particle_entang_viz.py (Entanglement Toy)

Pairs fly apart and "collapse" to correlated outcomes when either hits a detector line.

$$x_{t+1} = x_t + v_x, \quad y_{t+1} = y_t + v_y$$

$$\text{collapse when } x \le x_L \text{ or } x \ge x_R, \quad s_L = -s_R$$

QuantumStuff/Quantum.py (Classical Bit vs Qubit)

The qubit state is parameterized on a Bloch circle cross-section.

$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\phi}\sin\frac{\theta}{2}|1\rangle$$

$$P(0) = |a|^2, \quad P(1) = |b|^2$$

$$n_x = \sin\theta, \quad n_z = \cos\theta$$

QuantumStuff/quantum_particle_viz.py (2D Superposition)

A sum of stationary states produces a time-varying probability density.

$$\psi(x, y, t) = \sin(\pi x)\sin(\pi y)e^{-i2\pi t} + 0.6\sin(2\pi x)\sin(\pi y)e^{i1.5\pi t} + 0.4\sin(\pi x)\sin(2\pi y)e^{-i\pi t}$$

$$\rho = |\psi|^2, \quad \rho \leftarrow \rho / \sum \rho$$

QuantumStuff/quantum_search.py (Grover Toy)

The success probability oscillates with iteration count.

$$\sin\theta = \frac{1}{\sqrt{N}}$$

$$P_{\text{classical}}(k) = \min\left(\frac{k}{N}, 1\right)$$

$$P_{\text{Grover}}(k) = \sin^2\left((2k+1)\theta\right)$$

$$k^* \approx \frac{\pi}{4\theta} - \frac{1}{2}$$

QuantumStuff/quantum_slit_wave_viz.py (Wave Double Slit)

Two slit sources interfere to form a spatial intensity pattern.

$$\psi_{\text{in}} = \cos\left(k(x - x_0) - \omega t\right)$$

$$\psi_{1,2} = \frac{\cos(kr_{1,2} - \omega t)}{r_{1,2}^p}$$

$$I = (\psi_1 + \psi_2)^2$$

QuantumStuff/quantum_tunneling_viz.py (Split-Step Method)

A Gaussian packet interacts with a rectangular barrier; evolution uses split-step Fourier propagation.

$$\psi(x,0) = \left(\frac{1}{\pi\sigma^2}\right)^{1/4} e^{-(x-x_0)^2/(2\sigma^2)} e^{ik_0 x}$$

$$V(x) = \begin{cases} V_0, & |x| < \frac{w}{2} \\ 0, & \text{otherwise} \end{cases}$$

$$\psi(t + \Delta t) = e^{-iV\Delta t/2}\, \mathcal{F}^{-1}\left[e^{-ik^2\Delta t/2}\, \mathcal{F}\left(e^{-iV\Delta t/2}\psi(t)\right)\right]$$

$$P_{\text{left}} = \int_{x<-5} |\psi|^2\, dx, \quad P_{\text{right}} = \int_{x>5} |\psi|^2\, dx$$

QuantumStuff/quantum_wave_viz.py (Dispersing Packet)

A Gaussian packet drifts and spreads, illustrating dispersion.

$$\sigma(t) = \sqrt{\sigma_0^2 + (Dt)^2}$$

$$x_c = x_0 + Vt$$

$$\psi(x,t) = \exp\left[-\frac{(x - x_c)^2}{2\sigma(t)^2}\right] e^{i(K_0(x-x_c)-\omega t)}$$

QuantumStuff/relativistic_time_dilation_viz.py (Proper Time)

Proper time accumulates more slowly for a moving clock.

$$x(t) = x_0 + A\sin(\omega t), \quad v = A\omega\cos(\omega t)$$

$$\beta = \frac{v}{c}, \quad \gamma = \frac{1}{\sqrt{1 - \beta^2}}$$

$$d\tau = \frac{dt}{\gamma}$$

QuantumStuff/schrodinger_cat_viz.py (Decoherence Toy)

Coherence decays exponentially until collapse.

$$\mathcal{C}(t) = e^{-\Gamma t}$$

$$P_{\text{alive}} = 0.5 + 0.15 \sin(0.8t), \quad P_{\text{dead}} = 1 - P_{\text{alive}}$$

QuantumStuff/thermodynamics_laws_viz.py (Thermodynamics)

The panels illustrate equilibrium, energy bookkeeping, entropy increase, and the third law limit.

$$T_i(t) = T_{\text{target}} + \Delta_i e^{-0.35t}$$

$$\Delta U = Q - W$$

$$f_{\text{mix}} = 1 - e^{-0.25t}$$

$$T(t) = 320e^{-0.012t} + 2, \quad S = \ln(T + 1)$$

QuantumStuff/uncertainty_wavepacket_viz.py (Uncertainty Principle)

A breathing Gaussian illustrates $\Delta x \, \Delta p \gtrsim \hbar/2$.

$$|\psi(x)| = e^{-\frac{(x-\mu)^2}{2\sigma_x^2}}$$

$$|\phi(p)| = e^{-\frac{(p-p_0)^2}{2\sigma_p^2}}, \quad \sigma_p = \frac{1}{2\sigma_x} \; (\hbar = 1)$$

$$\Delta x \, \Delta p \approx \sigma_x \sigma_p$$

QuantumStuff/wormhole_viz.py (Wormhole Toy)

Particles spiral into a central throat and re-emerge on the other side.

$$\theta_{t+1} = \theta_t + \omega, \quad r_{t+1} = r_t - v_r$$

$$x = x_c + r\cos\theta, \quad y = y_c + r\sin\theta$$

$$\text{warp factor} = \frac{1}{1 + 0.4/r^2}$$

QuantumStuff/simple_harmonic_oscillator_viz.py (Mass–Spring)

A classic oscillator with total energy conserved.

$$\ddot{x} + \frac{k}{m}x = 0, \quad \omega_0 = \sqrt{\frac{k}{m}}$$

$$E = \tfrac{1}{2}mv^2 + \tfrac{1}{2}kx^2$$

QuantumStuff/damped_forced_oscillator_viz.py (Driven Oscillator)

Damping removes energy while the drive injects it, yielding steady-state oscillations.

$$\ddot{x} + 2\beta\dot{x} + \omega_0^2 x = \frac{F_0}{m}\cos(\omega_d t)$$

QuantumStuff/angular_momentum_viz.py (Central Force)

In a central potential, angular momentum is conserved.

$$\vec{F} = -k\vec{r}, \quad \vec{L} = m(\vec{r} \times \vec{v})$$

$$L_z = m(xv_y - yv_x), \quad \frac{d\vec{L}}{dt} = \vec{r} \times \vec{F} = 0$$

QuantumStuff/projectile_drag_viz.py (Quadratic Drag)

A projectile under gravity and drag follows a shorter, asymmetric trajectory.

$$m\frac{d\vec{v}}{dt} = -mg\,\hat{y} - c\,|\vec{v}|\,\vec{v}$$

QuantumStuff/two_body_orbit_viz.py (Newtonian Two-Body)

Two masses interact via inverse-square gravity, tracing bound orbits around the barycenter.

$$m_1\ddot{\vec{r}}_1 = Gm_1m_2\frac{\vec{r}_2 - \vec{r}_1}{|\vec{r}_2 - \vec{r}_1|^3}$$

$$m_2\ddot{\vec{r}}_2 = Gm_1m_2\frac{\vec{r}_1 - \vec{r}_2}{|\vec{r}_1 - \vec{r}_2|^3}$$

QuantumStuff/fluid_mechanics_channel_viz.py (Poiseuille Flow)

Laminar flow in a channel yields a parabolic velocity profile.

$$u(y) = U_{\max}\left(1 - \left(\frac{y}{H}\right)^2\right), \quad v = 0$$

QuantumStuff/maxwell_equations_viz.py (Maxwell's Equations)

A plane electromagnetic wave in vacuum satisfies the full Maxwell system.

$$\nabla \cdot \vec{E} = 0$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times \vec{B} = \mu_0\varepsilon_0\frac{\partial \vec{E}}{\partial t}$$