# Through Two Slits

## Methodological Note for a Temporal Visualizer of the Double-Slit Experiment and Its Descendants

**Version:** 1.0 **Date:** July 2026 **Artifact:** browser-based educational and research visualizer

## Purpose

This note defines the historical scope, mathematical model, interpretive boundaries, and reproducibility requirements for *Through Two Slits*. The visualizer is designed as a comparative instrument: the apparatus, detector domain, available information, and scientific question change across time. It does not imply that all selected experiments used an identical pair of physical slits.

> **Core rule.** The empirical display remains distinct from interpretation. Changing an interpretation tab may change explanatory language, but it must not change the calculated or recorded pattern.

# Scope and historical classification

| Date | Node | Object / apparatus | Historical role |
|---|---|---|---|
| 1801-1804 | Young interference | Light; two apertures / coherent portions | Canonical optical interference foundation. |
| 1924-1927 | Matter-wave bridge | de Broglie relation; electron diffraction context | Theory and experimental bridge, not represented as a literal double slit. |
| 1961 | Electron slits | Electrons; one to five microfabricated slits | Direct electron diffraction through fabricated slit systems. |
| 1989 | Single-electron buildup | Electron biprism; position-sensitive detector | Discrete detections accumulate into an interference distribution. |
| 1991 | Atomic double slit | Metastable helium atoms; microfabricated slits | Young-type interference extended to neutral atoms. |
| 1996-1998 | Which-path duality | Two-way atom interferometer; path marker | Quantifies the visibility-distinguishability trade-off. |
| 1999 | Fullerene interference | C60 molecules; material grating | Scale and complexity extension; experimental descendant. |
| 2000 | Delayed-choice quantum eraser | Entangled photons; coincidence sorting | Correlated subsets display fringe / anti-fringe behavior; raw signal does not. |
| 2012 | Quantum delayed choice | Quantum-controlled interferometer | Advanced descendant; avoids a forced classical open/closed apparatus choice. |
| 2023 | Temporal double slit | Time-modulated optical interface; spectral detector | Two time windows produce frequency-domain interference. |
| 2026 | Nanoparticle frontier | Sodium nanoparticles; optical gratings | Current scale frontier, explicitly not a literal two-slit apparatus. |

# 1. Mathematical model

For the spatial two-slit modes, the visualizer uses the Fraunhofer approximation for two identical rectangular slits. The normalized intensity is represented as an envelope multiplied by an interference term:

$$I(x) = \mathrm{sinc}^2(\pi a x / (\lambda L)) [1 + V \cos(2 \pi d x / (\lambda L) + \phi)] / 2$$

Here *a* is slit width, *d* is slit separation, *L* is propagation distance, *lambda* is wavelength, *phi* is relative phase, and *V* is fringe visibility. The browser implementation normalizes the sampled intensity array before drawing or generating events. This formula is a pedagogical far-field model, not a full electromagnetic or many-body solver.

## Matter waves

For massive objects the displayed wavelength is the de Broglie wavelength, **lambda = h/p**. Historical presets use object-appropriate orders of magnitude, but the visualizer deliberately exposes only a bounded pedagogical parameter space. It must not suggest that arbitrary combinations correspond to a feasible laboratory apparatus.

## Visibility, distinguishability, and decoherence

The interface uses the duality constraint $D^2 + V^2 \le 1$. A user-controlled path-information parameter contributes to distinguishability *D*; source coherence and environmental decoherence reduce the achievable visibility. The implementation computes a conservative visibility below the inequality bound rather than forcing equality in all cases.

A convenient simulation mapping is $V = C \exp(-3 \gamma) \sqrt{1-D^2}$, where *C* is source coherence and *gamma* is a dimensionless decoherence control. This mapping is an interface model, not a claim of universal microscopic decoherence dynamics.

## Event accumulation

Individual detections are sampled from the normalized probability distribution using a cumulative distribution function. Each event is local and discrete. The event cloud is vertically jittered only for visibility; the corresponding histogram and probability curve carry the quantitative meaning. Random seeds may be recorded when deterministic replay is required.

# 2. Apparatus-specific representations

## Young optical mode

Shows a coherent optical source, aperture system, propagated wavefronts, and a spatial intensity screen. The display supports one-slit and two-slit comparison and makes the single-slit diffraction envelope visible.

## Jönsson electron-slit mode

Supports one through five fabricated slits. The object label, wavelength scale, and detector semantics change to electrons. The renderer uses an N-slit array factor multiplied by a single-slit envelope.

## Tonomura single-electron mode

Represents an electron biprism rather than inaccurately drawing only two holes in a wall. The principal learning action is accumulation: isolated electron detections gradually approximate the probability distribution.

## Atomic and molecular modes

The helium-atom preset represents a Young-type microfabricated double slit. Fullerene and nanoparticle presets are labeled as descendants or frontiers and use grating-based apparatus diagrams. Their inclusion tracks extension in mass and complexity, not a single unbroken apparatus lineage.

## Delayed-choice quantum eraser

The visualizer separates the unsorted signal distribution from coincidence-selected subsets. Fringe and anti-fringe subsets cancel when combined. No interface animation may imply that a later detector setting changes an already recorded local signal distribution or permits controllable communication into the past.

## Temporal slit mode

The horizontal detector coordinate becomes frequency offset rather than spatial position. Two time gates separated by Delta t produce a spectral interference factor of the form **1 + V cos(omega Delta t)**, multiplied by the transform-limited spectral envelope of an individual time window. Spatial slit labels and centimeter units are removed in this mode.

## Quantum delayed choice

This advanced node is represented as a quantum-controlled interferometric configuration. It is not presented as evidence that a photon retrospectively chose to have always been a wave or particle; the interface emphasizes experimental statistics and control correlations.

# 3. Interpretive boundaries and misconception controls

| Claim | Visualizer response |
|---|---|
| "Consciousness collapses the wave." | The display identifies physical coupling, path marking, entanglement, and environmental decoherence. Human awareness is not a simulation variable. |
| "The electron is an ordinary wave spread across the detector." | Each registered event is local; the probability distribution governs the aggregate. |
| "The quantum eraser rewrites the past." | Raw and postselected distributions are displayed separately, with coincidence sorting shown explicitly. |
| "The double slit proves one interpretation." | Interpretation tabs explain alternative ontologies while leaving empirical predictions unchanged. |
| "Large objects cannot interfere." | The scale timeline distinguishes practical decoherence and coherence constraints from a categorical classical boundary. |

## Interpretation tabs

Operational quantum mechanics, Copenhagen-family approaches, many-worlds, de Broglie-Bohm, objective-collapse models, relational approaches, and quantum-information approaches are presented as interpretive frameworks. The text must clearly distinguish established predictions from ontological claims and open questions.

# 4. Reproducibility and data export

Every run exports a JSON record containing: timeline node, mode classification, apparatus type, object, wavelength or spectral scale, slit or gate parameters, path-information setting, coherence, decoherence, event count, visibility, distinguishability, random seed when used, timestamp, and software version. The export should permit a second browser session to reconstruct the same parameter state.

> Annotations are stored locally in the browser and are not transmitted to a server. The user can export and import annotation JSON. The interface must state that clearing browser storage can remove unexported annotations.

# 5. Validation protocol

| Test | Acceptance criterion |
|---|---|
| Symmetry | At zero phase and symmetric slits, I(x) is symmetric within numerical tolerance. |
| One-slit limit | Disabling one slit removes the two-path interference factor while retaining diffraction envelope. |
| Path-information limit | As D approaches 1, visibility approaches 0 and the distribution tends toward an incoherent sum. |
| Decoherence monotonicity | Increasing the decoherence control cannot increase calculated visibility. |
| Event convergence | Large event samples converge visually and statistically toward the probability distribution. |
| Quantum eraser accounting | Fringe and anti-fringe subsets combine to a non-interfering unsorted distribution. |
| Temporal scaling | Increasing temporal separation decreases spectral fringe spacing. |
| Responsive layout | The simulation remains operable at 320 CSS pixels without horizontal page overflow. |
| Accessibility | All controls have visible labels; keyboard focus and reduced-motion preference are respected. |

# Known limitations

The visualizer is not a laboratory-control package, finite-difference electromagnetic solver, path-integral engine, density-matrix tomography platform, or reconstruction of complete historical hardware. Distances and component geometries are illustrative unless a node explicitly labels a measured value from the cited experiment. Apparatus animations are explanatory diagrams; the detector distributions and exported parameters are the quantitative layer.

The timeline is selective. It highlights experiments that materially expand the two-slit problem through object scale, single-event detection, path information, entanglement, quantum control, or temporal modulation. It is not a complete history of interferometry.

# 6. Primary references

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12. Pedalino, S., Ramirez-Galindo, B. E., Ferstl, R., et al. (2026). Probing quantum mechanics with nanoparticle matter-wave interferometry. *Nature*, 649, 866-870. https://doi.org/10.1038/s41586-025-09917-9

## Reference policy

Primary publications are preferred for experimental claims. Secondary sources may be used only for orientation or historiographic context and must not replace the original apparatus description when the primary publication is available.