Embodied Quantum Pedagogy through Krump Street Dance, Laban Movement Analysis, and String Diagrams

Arun Nadarasa
Angels of Krump Movement Federation
https://arunnadarasa.github.io/quantumkrump/

Dakota Simao
Twin Bad Liks / Jr Outrage
Artistic Director & Choreographer, Geneva
https://www.youtube.com/@dakotasimao

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Abstract

Introductory quantum information science (QIS) concepts—coherent superposition, nonlocal entanglement, and relative phase interference—remain cognitively inaccessible to nonspecialist learners when introduced solely through matrix algebra, yet naive classical analogies frequently entrench persistent misconceptions. We present *Quantum Krump*, an embodied movement curriculum, open-source web toolkit, and theatrical dramaturgical framework that grounds QIS pedagogy in authentic South Central Los Angeles Krump street dance, Laban Movement Analysis (LMA), and diagrammatic applied category theory. First, we map Laban's four Effort Factors (*Weight*, *Time*, *Space*, *Flow*) and eight composite Effort Actions onto Krump's foundational vocabulary (`STOMP`, `JAB`, `CHEST POP`, `ARM SWING`), vertical spatial levels (`LIVE`, `KRUMP`, `BUCK`), the right-handed 3D Bloch sphere kinesphere, and a 16-state binary-prefix affective emotion wheel across a 140–150 BPM metric lattice, explicitly bounding everyday classical metaphors against measurement collapse and phase coherence. Second, via categorical delooping from solo posture quivers (CatKS) to a dagger-compact symmetric monoidal category $(\mathcal{C}_{\mathrm{Krump}}, \otimes, I, \sigma, \eta_D, \epsilon_D)$ compiled in DisCoPy, we formalize concurrent partner duets, bifunctorial interchange, snake yanking identities, and unitary circuit compilation ($\mathcal{F}_{\mathrm{DisCo}}$). Third, co-created with choreographer Dakota Simao, we introduce *11th Quantum Dimension*, a four-act, 20-dancer theatrical staging architecture that translates classical bits, superposition, trauma-bond entanglement, and $\Delta\varphi = \pi$ destructive-interference de-escalation into a trauma-informed social narrative on domestic violence. Computational verification on Quantinuum's `Helios-1E-lite` trapped-ion emulator (2,048 emulator shots; 0 physical QPU shots claimed) confirms blinded quality control ($\Delta = 0.0009$), 99.41% Clifford-projected partner duet readout fidelity, and collision-free OpenJij stage scheduling ($E_0 = -7.3569$), strictly contextualized by Sandia QUOPS volumetric flooring ($Q = 256$; $1.74\,\mu$s 4-qubit and $0.33\,\mu$s 1-qubit CPU evaluation). Finally, we report formative studio co-design insights ($N = 0$ human-subjects efficacy claims to date) alongside a two-phase evaluation roadmap pairing an $N \geq 90$ multilingual QISCIT psychometric calibration pilot with a pre-registered $N = 60$–100 two-arm randomized controlled study.

1 Introduction and Cultural Lineage

Teaching introductory quantum information science (QIS) without calculus or linear algebra poses a well-documented pedagogical dilemma [1, 2]. Purely symbolic treatments alienate learners outside physics and computer science, whereas unguarded everyday metaphors—comparing

superposition to a "dimmer switch" or entanglement to "matching socks"—conflate quantum amplitudes with classical mixtures and obscure relative phase φ. Conversely, research in embodied physics and arts-integrated STEAM education demonstrates that structured kinesthetic enactment builds durable sensorimotor anchors for abstract scientific transformations [3,4]. Pioneering quantum dance interventions such as *The 2-Qubit Dance* [5], *Dancing with Pauli* [6], and *Dunamis Novem* [7] showed that bodily orientation can illustrate single-qubit rotations and measurement. Yet existing interventions rely predominantly on classical balletic postures or isolated theatrical mime, lacking a formal compositional grammar, explicit classical computational bounds, and grounding in an authentic street-dance lineage.

Quantum Krump addresses these gaps by uniting three mutually reinforcing pillars: (1) authentic Krump street dance [8], (2) Laban Movement Analysis (LMA) [9, 10], and (3) diagrammatic categorical quantum mechanics [11–14]. Originating at the Quantinuum Bradford Hackathon 2025 [15] as a contribution to the UNESCO International Year of Quantum Science and Technology (IYQ 2025) [16] alongside the Indian Krump Festival (IKF) and Point Blank Fam communities, the curriculum powers an open-source digital ecosystem comprising interactive facilitator/student workbooks (`https://quantumworkshop.lovable.app/`), a quantum-inspired Krump beat lab (`https://ikfquantum.lovable.app/`), and the StreetKode Quantum battle scoring platform (`https://streetkodequantum.lovable.app/`).[1]

Krump Street Dance Lineage. Krump emerged in the early 2000s in South Central Los Angeles, created by Ceasare "Tight Eyez" Willis and Jo'Artis "Big Mijo" Ratti alongside pioneers Marquisa "Miss Prissy" Gardner, Christopher "Lil C" Toler, and Jason "Slayer" Green [8]. Born as a cathartic, non-violent alternative to street violence and structural marginalization, Krump channels intense emotional storytelling into disciplined somatic release. Its movement vocabulary rests on four cardinal foundations—`STOMP` (percussive downward foot strike), `JAB` (sharp linear arm extension), `CHEST POP` (explosive upward/forward thoracic contraction-release), and `ARM SWING` (broad centrifugal arm sweep)—executed across three vertical spatial levels: `LIVE` (elevated, upright posture), `KRUMP` (athletic mid-level stance), and `BUCK` (deeply grounded crouch). Session circles rely on continuous rhythmic *groove*, collective peer amplification (*hype*), low rebounds (*buck hops*), battle-ending climaxes (*kill-offs*), and mentorship within a *fam* led by a *Big Homie*.

Laban Movement Analysis and Bloch Geometry. Rudolf Laban and F. C. Lawrence decomposed movement dynamics into four polar *Effort Factors* [9]: **Weight** (*Strong* vs. *Light*), **Time** (*Sudden* vs. *Sustained*), **Space** (*Direct* vs. *Indirect*), and **Flow** (*Bound* vs. *Free*), whose Weight–Time–Space polarities generate $2^3 = 8$ Basic Effort Actions. In parallel, a pure single-qubit state in $\mathbb{C}^2$ (modulo global phase) is parameterized on the unit Bloch sphere ($r = 1$) [18,19] by colatitude $\theta \in [0, \pi]$ and azimuthal phase $\varphi \in [0, 2\pi)$:

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

while interior points ($r < 1$) represent mixed states ρ ($\mathrm{Tr}(\rho^2) < 1$) arising either from environmental decoherence or from tracing out an entangled partner subsystem [20].

2 Instructional Design, Accessibility, and Bounded Bloch Drills

The workshop operates as a minute-by-minute modular score adaptable across 60-, 75-, and 90-minute formats (Table 1). Learners pair into two-arm-distance dyads alternating between

[1] This focused 15-page paper isolates the embodied pedagogy, categorical composition, theatrical dramaturgy, and evaluation design of *Quantum Krump*. Readers interested in monocular 3D human motion recovery and humanoid robot control are referred to our standalone Physical AI companion paper [17]; full multi-platform computational appendices appear in the omnibus reference monograph.

Role A (state preparation and posture maintenance) and **Role B** (unitary transformation call or projective measurement trigger). Drawing on multimodal instructional presentation [21] and physiological/psychological safety sequencing [22], every physical drill includes a full seated adaptation: `STOMP` and `BUCK` translate to sharp palm-to-thigh strikes or heel drops, *Press* to sustained armrest pushes, and *Glide* to smooth linear torso leans.

Table 1: Workshop phase allocation across 60-, 75-, and 90-minute instructional formats.

Session Phase & Pedagogical Objective	**60 min**	**75 min**	**90 min**
1. Arrival, Safety Pacing & Cultural Context (Krump Lineage)	5 min	7 min	10 min
2. Warm-Up & Laban Space Attunement (`LIVE`/`KRUMP`/`BUCK`)	8 min	10 min	12 min
3. Effort Lab: Weight, Time, Space & Flow Polarities	10 min	12 min	14 min
4. Concept Labs: Superposition, Multi-Basis Entanglement, Interference	15 min	18 min	20 min
5. Bloch Sphere Directional Lab (Right-Handed 3D Kinesphere)	7 min	8 min	10 min
6. Phrase Building on the Quantum Map, Duets & Yoneda Circle	8 min	11 min	12 min
7. Epistemic Debrief, Bounded Analogies & Cohort Certification	7 min	9 min	12 min

Bounded Analogies and Core Concept Drills. Rather than avoiding everyday analogies, facilitators introduce two familiar pictures and explicitly interrogate where they break down:

- **Dimmer Switch vs. Projective Collapse:** Unlike a classical dimmer that remains at 50% brightness when inspected, a dancer hovering dynamically between `LIVE` ($|0\rangle$) and `BUCK` ($|1\rangle$) snaps non-deterministically into a single discrete level upon Role B's percussive call ("HIT!"), enacting Born-rule probabilities $\cos^2(\theta/2)$ and $\sin^2(\theta/2)$.
- **Spinning Coin vs. Relative Phase Interference:** Unlike a spinning coin whose hidden classical trajectory lacks phase, two facing dancers pulsing thoracic `CHEST POP`s at matched tempo demonstrate constructive amplification in phase ($\Delta\varphi = 0$, $|A + A|^2 = 4|A|^2$) and destructive cancellation into stillness in anti-phase ($\Delta\varphi = \pi$, $|A - A|^2 = 0$).
- **Multi-Basis Entanglement Drill:** Partners prepare $|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$ facing away from each other to prevent visual cueing. Operationally, on Beat 3 of each bar the facilitator calls the measurement axis $M \in \{Z, X\}$, while the studio audio loop triggers a stochastic percussive sample on Beat 4—low kick drum (`0` $\rightarrow$ `LIVE` in Z or `FORWARD` in X) versus crisp snare rimshot (`1` $\rightarrow$ `BUCK` in Z or `BACK` in X)—enacting a single random shared outcome across whichever basis was selected. Facilitators demonstrate that matching outcomes solely along Z could be mimicked by a static classical lookup table, whereas preserving correlation dynamically across both $Z \otimes Z$ and $X \otimes X$ illustrates multi-basis stabilizer correlation ($|++\rangle, |--\rangle$), while explicitly noting during debrief that shared room acoustics enact correlation structure without claiming space-like Bell non-locality and that genuine CHSH violation ($\mathcal{S} = 2\sqrt{2} > 2$) requires $\pi/4$ planar offsets ($\cos^2(\pi/8) \approx 85.4\%$ vs. 75% classical local bound) [19].

3D Bloch Kinesphere and Exponential Register Scaling. Figure 1 maps the Bloch sphere onto a right-handed studio coordinate system: $+Z$ (`LIVE`, $|0\rangle$), $-Z$ (`BUCK`, $|1\rangle$), $+X$ (audience-forward, $|+\rangle$), $-X$ (upstage-back, $|-\rangle$), $+Y$ (stage left, $|+i\rangle$), and $-Y$ (stage right, $|-i\rangle$). Instructors clarify that physical reach amplitude is choreographic projection rather than $r > 1$, and contrast $n \in \{1, 2, 3, 4\}$ studio registers ($2, 4, 8, 16$ basis states) against classical statevector memory frontiers ($n = 40 \implies 2^{40} \approx 1.10 \times 10^{12}$ states requiring ~ 16 TB RAM in `complex128`; $n = 80 \implies 1.21 \times 10^{24}$; $n = 270 \implies 1.90 \times 10^{81}$, exceeding observable-universe atom counts) while distinguishing physical vs. logical qubits and exact simulators vs. noise-modeled hardware emulators.

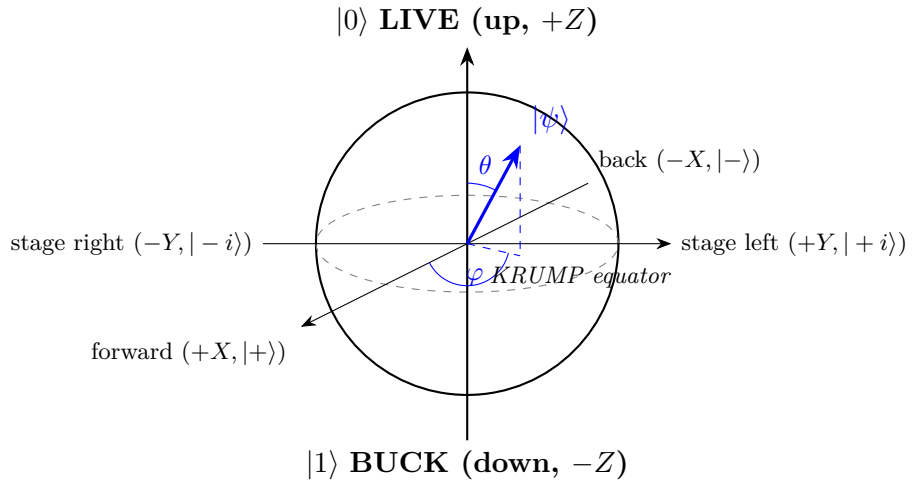


Figure 1: The Bloch sphere mapped onto the dancer's 3D kinesphere ($\hat{x}_{\text{forward}} \times \hat{y}_{\text{stage left}} = \hat{z}_{\text{up}}$). Colatitude $\theta \in [0, \pi]$ spans `LIVE` ($|0\rangle$) to `BUCK` ($|1\rangle$); equatorial phase $\varphi \in [0, 2\pi)$ spans $+X$ ($|+\rangle$), $+Y$ ($|+i\rangle$), $-X$ ($|-\rangle$), and $-Y$ ($|-i\rangle$). Instructors emphasize that pure states lie strictly on $r = 1$, whereas $r < 1$ denotes decohered or locally reduced entangled states.

Anatomical Origin, Affine Level Mapping, and Stage-Fixed Frame. Three biomechanical conventions ensure every basis and phase state is kinesthetically executable without joint strain or frame ambiguity: (i) *Pelvic Origin & Affine Levels:* anchoring $(0, 0, 0)$ at the neutral mid-stance pelvic/umbilical center ($z = h_0$, shifting to the mid-sternum in seated adaptations) rather than the floor maps vertical height $z \in [h_{\min}, h_{\max}]$ via $\cos\theta = \frac{2z-(h_{\max}+h_{\min})}{h_{\max}-h_{\min}} \in [-1, +1]$, keeping both $+Z$ ($|0\rangle$, `LIVE`, $z = h_{\max}$) and antipodal $-Z$ ($|1\rangle$, `BUCK`, $z = h_{\min}$) physically reachable above the floor; (ii) *Bloch Double Cover (180° vs. 90°):* because $\text{SU}(2) \to \text{SO}(3)$ doubles Hilbert-space angles ($\theta_{\text{Bloch}} = 2\vartheta_{\text{Hilbert}}$), orthogonal basis states are 180° antipodes ($+Z$ vs. $-Z$) rather than 90° perpendiculars, preventing learners from conflating a horizontal 90° equatorial reach ($\theta = \pi/2$, equal superposition) with $|1\rangle$; and (iii) *Stage-Fixed Frame & Posterior Reach:* locking ($\hat{x}_{\text{forward}}, \hat{y}_{\text{stage left}}$) allocentrically to the audience wall prevents torso rotation from masquerading as phase evolution and lets dancers enact $-X$ ($|-\rangle$, $\varphi = \pi$) via an upstage step-back, dorsal thoracic `CHEST POP` recoil, or posterior elbow strike without glenohumeral shoulder hyperextension.

3 The Laban × Krump × Quantum Compositional Map and Metric Lattice

Figure 2 and Table 2 establish the compositional bridge from isolated Effort Factors to Laban's eight three-factor Effort Actions ($2^3 = 8$). In pedagogical scaffolding, **Time** governs quantum operational character: *sudden* actions (*Punch*, *Slash*, *Dab*) enact rapid projective collapse or ancilla sampling, whereas *sustained* actions (*Press*, *Glide*, *Float*) enact continuous unitary rotations and adiabatic phase evolution.

Reconciling the Dual Pedagogical Role of `STOMP`. Instructors explicitly distinguish two operational contexts so solo gate compilation never conflicts with dyadic measurement drills: in isolated Effort drills, a forceful downward `STOMP` embodies the percussive jolt of projective collapse into a grounded eigenstate; in unitary phrase compilation ($\mathcal{F}_{\text{DisCo}}$, Section 4), the opening `STOMP` acts as the phrase-launching Hadamard gate H, kicking the dancer out of static rest $|0\rangle$ into balanced kinetic superposition $|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$ before a terminal `KILL-OFF` projectively

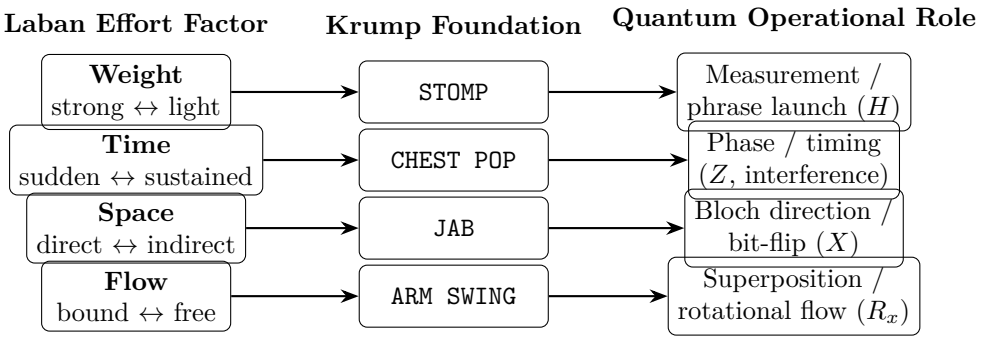


Figure 2: Three-way pedagogical correspondence linking Laban Effort Factors, Krump foundations, and quantum operational roles.

collapses the sequence.

Table 2: Laban's Eight Basic Effort Actions mapped to Krump cues and quantum mechanics.

Action	Weight	Time	Space	Krump Physical Cue	Quantum Interpretation
Punch	Strong	Sudden	Direct	Direct jab or floor strike	Projective collapse onto eigenstate
Slash	Strong	Sudden	Indirect	Wide centrifugal arm cut	Rapid collapse out of wide superposition
Press	Strong	Sustained	Direct	Slow `BUCK` floor push	Continuous unitary polar rotation $R_y(\theta)$
Wring	Strong	Sustained	Indirect	Opposing torso–pelvic torque	Internal anatomical subsystem coupling
Dab	Light	Sudden	Direct	Crisp wrist pop or foot tap	Weak measurement / ancilla probe
Flick	Light	Sudden	Indirect	Light finger/wrist flicks in `LIVE`	Multi-axis azimuthal phase scattering
Glide	Light	Sustained	Direct	Smooth linear floor travel	Adiabatic state transport along axis
Float	Light	Sustained	Indirect	Suspended drift across levels	Unperturbed coherent superposition

Quantum Beats and the 140–150 BPM Metric Lattice. For a normalized two-level superposition $|\Psi(t)\rangle = c_1 e^{-i\omega_1 t}|E_1\rangle + c_2 e^{-i\omega_2 t}|E_2\rangle$ with complex amplitudes $c_k = |c_k|e^{i\phi_k}$ ($|c_1|^2 + |c_2|^2 = 1$), spatial probability density oscillates at the Bohr beat frequency $\Delta\omega = \omega_2 - \omega_1$, mirroring 3-against-4 polyrhythmic arm cross-rhythms layered over a 4/4 Krump bassline. Within Krump's canonical 140–150 BPM tempo corridor ($T_{\text{meas}} = 1.655$ s and $\tau_{\text{beat}} = 413.8$ ms at 145 BPM), the four quarter-note beats anchor discrete azimuthal phases: Beat 1 ($\varphi = 0$, `STOMP`, $+1$), Beat 2 ($\varphi = \pi/2$, `JAB`, $+i$), Beat 3 ($\varphi = \pi$, `CHEST POP`, -1 anti-phase), and Beat 4 ($\varphi = 3\pi/2$, `ARM SWING`, $-i$).

Hierarchical n-Qubit Emotion Wheel and Subsystem Partitioning. Developed with the Point Blank Fam and grounded in empirical Laban–emotion correspondences [10, 23], our binary-prefix emotion wheel encodes 2^n storytelling states ($n \in \{1, 2, 3, 4\}$) as a context-dependent decision tree (Table 3): q_1 sets physiological arousal (`0` low vs. `1` high), q_2 branches into four root families (`00` *Sad*, `01` *Fearful*, `10` *Angry*, `11` *Happy*), q_3 sets relational projection (`0` defensive/recoil vs. `1` outward/dominant, subdividing low-arousal negative `00` into passive withdrawal `000` *Sad* vs. active visceral rejection `001` *Disgusted* and high-arousal `10` into startled recoil `100` *Surprised* vs.

dominant assertion `101` *Angry*), and q_4 refines somatic discharge across 16 nuances. When two back-to-back partners synchronize via a shared two-beat percussive cue $(b_1, b_2) \in \{0,1\}^2$ across all four $n = 2$ root emotions, they enact a **four-qubit transversal Bell register**:

$$|\Phi^+\rangle_{A_1B_1} \otimes |\Phi^+\rangle_{A_2B_2} = \frac{1}{2} \sum_{x\in\{0,1\}^2} |x\rangle_{A_1A_2} \otimes |x\rangle_{B_1B_2} = \frac{|0000\rangle + |0101\rangle + |1010\rangle + |1111\rangle}{2}_{A_1A_2B_1B_2}, \tag{2}$$

guaranteeing uniform correlation across all four affective states, in contrast to a 4-qubit GHZ state $\frac{|0000\rangle+|1111\rangle}{\sqrt{2}}$ which would restrict outcomes to only *Sad* (`00`) and *Happy* (`11`).

Table 3: Hierarchical binary-prefix encoding for the n-qubit emotion wheel ($n \in \{1, 2, 3, 4\}$).

Register	**Prefix / Bits**	**Affective State**	**Krump / Laban Choreographic Expression**
$n = 1$	`0` / `1`	Sad / Happy	Grounded heavy `BUCK` gaze down vs. open-chest `LIVE` bounce.
$n = 2$	`00` / `01`	Sad / Fearful	Melancholic stillness vs. guarded chest recoil.
	`10` / `11`	Angry / Happy	Explosive forward jabs vs. exuberant wide arm swings.
$n = 3$	`000`, `001`, `010`, `011`	Sad, Disgusted, Fearful, Bad	Low drop; thoracic rejection; evasive footwork; gritty `BUCK` grind.
	`100`, `101`, `110`, `111`	Surprised, Angry, Calm, Happy	Suspended recoil; stomp flurry; steady breath groove; double arm lift.
$n = 4$	`0000` / `0001`	Lonely / Depressed	Isolated inward stillness vs. slow sinking drop into floor.
	`0010` / `0011`	Vulnerable / Ashamed	Exposed thoracic center vs. shielded face and shoulder collapse.
	`0100` / `0101`	Terrified / Anxious	Trembling defensive cross vs. restless hyper-accelerated shifts.
	`0110` / `0111`	Guilty / Numb	Aborted forward reaches vs. rigid mechanical groove without breath.
	`1000` / `1001`	Shocked / Defiant	Frozen dilated lock vs. defensive grounded `BUCK` brace.
	`1010` / `1011`	Enraged / Hostile	Heavy outward stomps vs. direct biting jabs cutting space.
	`1100` / `1101`	Serene / Grounded	Fluid sweeping arm glides vs. deep bass-resonant centered bounce.
	`1110` / `1111`	Playful / Proud	Syncopated buck hops vs. triumphant radiant double chest pop.

4 Applied Category Theory and DisCoPy Dagger-Compact Duets

Extending categorical musicology and gesture theory [24–28], we organize choreographic syntax at two levels: solo quiver paths and concurrent monoidal string diagrams.

Solo Quivers (CatKS $\to$ CatKP**) and the Yoneda Circle.** The free category CatKS is generated by six level-tagged forms:

$$V = \big\{\texttt{STOMP}_{\text{BUCK}},\ \texttt{CHEST POP}_{\text{KRUMP}},\ \texttt{JAB}_{\text{LIVE}},\ \texttt{ARM SWING}_{\text{KRUMP}},\ \texttt{BUCK HOP}_{\text{BUCK}},\ \texttt{KILL-OFF}_{\text{BUCK}}\big\}, \tag{3}$$

together with seven canonical studio transitions (f : $\texttt{STOMP}_{\text{BUCK}} \to \texttt{CHEST POP}_{\text{KRUMP}}$, g : $\texttt{CHEST POP}_{\text{KRUMP}} \to \texttt{JAB}_{\text{LIVE}}$, h : $\texttt{JAB}_{\text{LIVE}} \to \texttt{KILL-OFF}_{\text{BUCK}}$, j : $\texttt{ARM SWING}_{\text{KRUMP}} \to$

$\texttt{CHEST POP}_{\text{KRUMP}}$, $k : \texttt{BUCK HOP}_{\text{BUCK}} \to \texttt{CHEST POP}_{\text{KRUMP}}$, $l : \texttt{STOMP}_{\text{BUCK}} \to \texttt{ARM SWING}_{\text{KRUMP}}$, and $m : \texttt{CHEST POP}_{\text{KRUMP}} \to \texttt{ARM SWING}_{\text{KRUMP}}$), trivial groove identities id_A, and beat-counting repetition endomorphisms $r_A^k \in (\mathbb{N}, +, 0)$. Round-indexed functors $F_r : \text{CatKS} \to \text{CatKP}$ ($r \in \{1, 2, 3\}$) map structural forms to round-contextualized battle state classes and lift timeline phrases $P : [0, n] \to \text{CatKS}$ via ordinal path composition $F_r \circ P$ while preserving associativity and identities (Figure 3). By the Yoneda Lemma ($Y(A) = \text{Hom}_{\text{CatKS}}(-, A)$, the set of incoming transitions terminating at posture A) [11], a central dancer holding `CHEST POP` while surrounding dancers enter via f (from `STOMP`), j (from `ARM SWING`), and k (from `BUCK HOP`) demonstrates kinesthetically that aesthetic meaning is relational—with facilitators noting that $\text{Hom}_{\text{CatKS}}(-, A)$ is a discrete set in **Set** rather than a linear Hilbert-space superposition.

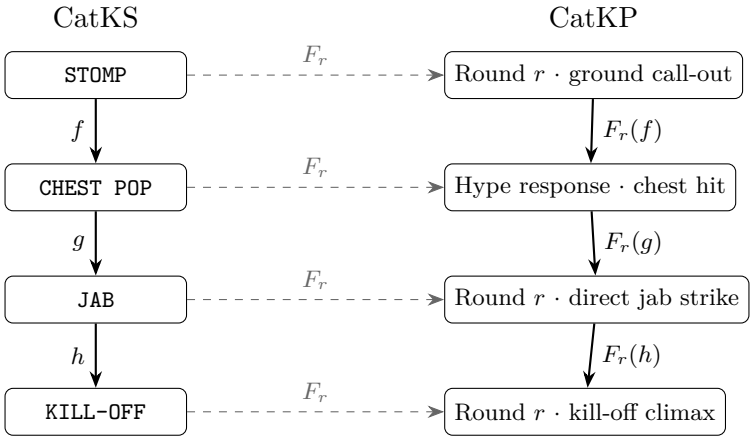


Figure 3: Round-indexed functor $F_r : \text{CatKS} \to \text{CatKP}$ mapping solo transitions to performed battle events.

Categorical Delooping to Dagger-Compact Monoidal Duets ($\mathcal{C}_{\text{Krump}}$). To model concurrent partners, we perform a categorical delooping lift into a free dagger-compact symmetric monoidal category $(\mathcal{C}_{\text{Krump}}, \otimes, I, \sigma, \eta_D, \epsilon_D)$ equipped with a special commutative Frobenius algebra $(\delta, \mu, \iota, \zeta)$ (comultiplication δ, multiplication μ, unit $\iota : I \to D$, and counit $\zeta : D \to I$) on self-dual dancer object D ($D^* \cong D$) and compiled in DisCoPy [12, 14, 29]. Movements lift from vertices to 1-morphisms $f : D \to D$ along vertical time wires, unlocking parallel tensor juxtaposition $D \otimes D$:

1. **Bifunctorial Interchange:** $(f_2 \circ f_1) \otimes (g_2 \circ g_1) = (f_2 \otimes g_2) \circ (f_1 \otimes g_1)$ guarantees that independent partner sequences commute with synchronized beat-by-beat duet layering, verified to identical normal form in DisCoPy (Figure 4a).

2. **Entanglement Cap, Climax Cup, and Snake Yanking:** $\eta_D : I \to D \otimes D$ initiates an entangled duet from silence I, $\epsilon_D : D \otimes D \to I$ executes a synchronized joint kill-off, $\sigma_{D,D}$ swaps stage tracks ($\sigma^2 = \text{id}_{D \otimes D}$), and Frobenius spiders (δ, μ) model session hype branching and convergence. Syntactically in $\mathcal{C}_{\text{Krump}}$, the snake equation $(\epsilon_D \otimes \text{id}_D) \circ (\text{id}_D \otimes \eta_D) = \text{id}_D$ yanks an entangled momentum transfer straight to solo propagation id_D (Figure 4c); under normalized unitary circuit semantics in **FHilb**, contraction carries the standard post-selected teleportation scalar $\frac{1}{2}\,\text{id}_{\text{qubit}}$ (1/4 probability without classical Pauli feedforward).

Evaluating unitary phrase cores inside **FHilb** and extending to terminal projective projections in **PFHilb**, the monoidal functor $\mathcal{F}_{\text{DisCo}} : \mathcal{C}_{\text{Krump}} \to \textbf{PFHilb}$ maps $D \mapsto$ qubit, `STOMP` $\mapsto H$, `JAB` $\mapsto X$, `CHEST POP` $\mapsto Z$, `ARM SWING` $\mapsto R_x(\pi/2)$, `BUCK HOP` $\mapsto R_z(\pi/2)$, Hermitian post-selection `KILL-OFF` $\mapsto |0\rangle\langle 0|$, $\eta_D \mapsto \text{Ket}(0, 0) \gg (H \otimes \text{id}) \gg CX$, and $\epsilon_D \mapsto CX \gg (H \otimes \text{id}) \gg \text{Bra}(0, 0)$ (Table 4; it also compiles to 16k-parameter DisCoPy Tiny Recursive Message Passing schemas for collision-free routing [30]).

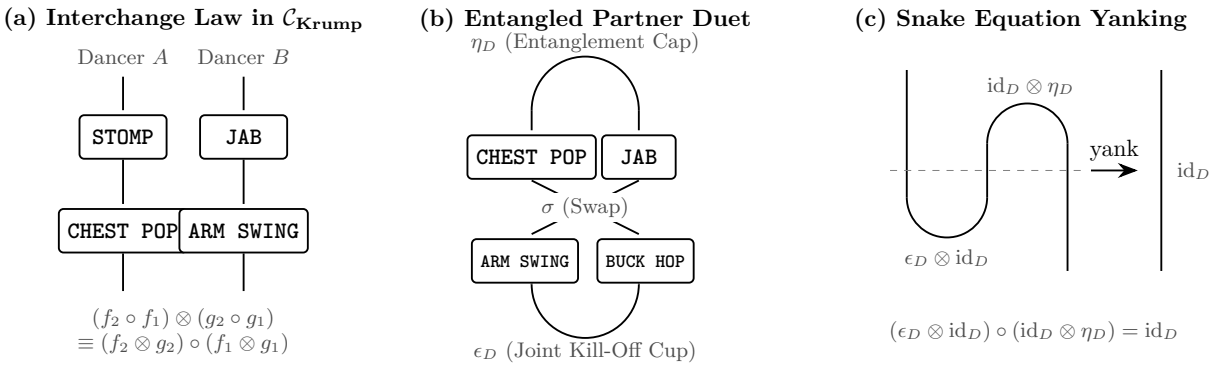


Figure 4: Monoidal string diagrams in $\mathcal{C}_{\text{Krump}}$ verified in DisCoPy [14]: (a) Bifunctorial interchange; (b) 5-layer entangled duet (η_D, CHEST POP $\otimes$ JAB, σ, ARM SWING $\otimes$ BUCK HOP, ϵ_D); (c) Topological snake yanking across an intermediate horizontal $D^{\otimes 3}$ slice.

Table 4: Summary of verified algebraic identities in $\mathcal{C}_{\text{Krump}}$ via DisCoPy [14].

Categorical Structure	**DisCoPy Object**	**Verification**	**Studio & Quantum Meaning**
Bifunctorial Interchange	$(f_2 \circ f_1) \otimes (g_2 \circ g_1)$	`normal_form()` equal	Independent partner phrasing commutes with beat-locked duet layers.
Dagger Cap & Cup	$\eta_D,\ \epsilon_D$	$P(\|00\rangle) = P(\|11\rangle) = 0.5$	Bell-pair duet initiation from silence and synchronized `KILL-OFF`.
Snake Equations	$(\epsilon_D \otimes \mathrm{id}_D) \circ (\mathrm{id}_D \otimes \eta_D)$	Reduces to id_D	Entangled partner momentum transfer yanks to solo track ($\frac{1}{2}\mathrm{id}_{\text{qubit}}$ in **FHilb**).
Symmetric Swap	$\sigma_{D,D}$	$\sigma^2 = \mathrm{id}_{D\otimes D}$	Stage crossover without collision; involutive hypergraph equality.
Frobenius Spiders	$\delta = \text{Spider}(1,2),\ \mu = \text{Spider}(2,1)$	Spider fusion holds	Lead-dancer hype radiation and collective ensemble convergence.

5 Dramaturgical Translation: *11th Quantum Dimension*

Bringing QIS from studio workshops to general theatrical audiences requires transcending algebraic vocabulary altogether. Co-developed with choreographer **Dakota Simao** (*Twin Bad Liks / Jr Outrage*)—whose Krump-contemporary work on domestic violence earned the Golden Buzzer on *La France a un Incroyable Talent* and surpassed 300 million views worldwide [31–34]—*11th Quantum Dimension* is a 60-minute, four-act staging architecture and completed digital pre-visualization for up to 20 dancers (Table 5).

Somatic Decoding of Quantum Mechanics via Interpersonal Narrative. Non-technical dancers and audiences decode five core QIS structures through the lived arc of interpersonal entrapment and liberation: (1) **Classical Bits (0 vs. 1)** enact the rigid deterministic cycle of silent compliance ($|0\rangle$) versus explosive outburst ($|1\rangle$) in linear corridors; (2) **Continuous Qubits** open the 3D emotional Bloch kinesphere across polar elevation θ and azimuthal intention φ; (3) **Superposition ($\alpha|0\rangle + \beta|1\rangle$)** enacts polyrhythmic bodily counterpoint—pleading contemporary upper-body reach coexisting simultaneously with defensive `BUCK` lower-body grounding—until a sudden external shock acts as measurement operator $\hat{M}$ collapsing the state; (4) **Entanglement ($|\Phi^+\rangle$)** enacts non-separable trauma bonding across a split stage, where Dancer A's recoil stage-left instantaneously correlates with Dancer B's involuntary response stage-right without physical contact; and (5) **Destructive Phase Interference ($\Delta\varphi = \pi$)** enacts non-violent de-escalation: rather than matching aggression in phase ($\Delta\varphi = 0 \implies 4|A|^2$ escalation), a deliberate π phase inversion into a grounded contemporary floor slide absorbs the kinetic vector to zero ($|A - A|^2 = 0$), breaking the cycle of violence.

Table 5: Four-act dramaturgical architecture of *11th Quantum Dimension* (60 min, 20 dancers).

Act	Duration / Cast	Spatial Geometry	Quantum & Somatic Mapping	Creative Tech Stack
Act I	00–15 min 20 dancers	Rigid linear corridors	**Classical Bits:** Binary deterministic entrapment ($\|0\rangle$ silence vs. $\|1\rangle$ outburst).	**ElevenLabs:** Monotone clinical voice. **Moth Quantum:** Binary clock pulses.
Act II	15–30 min Solos / trios	Elliptical constellations	**Qubits & Superposition:** Simultaneous love and terror; external shock collapse $\hat{M}$.	**ElevenLabs:** Polyphonic inner whispers. **Moth Quantum:** Bloch-angle drones.
Act III	30–45 min 10 duets	Split stage / non-local	**Entanglement ($\|\Phi^+\rangle$):** Non-separable trauma bond; instant cross-stage correlation.	**Three.js & Moth:** Scrim Bell-pair tethers & circuit-driven sub-bass.
Act IV	45–60 min Full ensemble	Concentric circles	**Interference ($\Delta\varphi = \pi$):** Conscious phase inversion absorbs force; liberating `KILL-OFF`.	**anime.js, ElevenLabs, Moth:** Collision-checked vector paths & choral release.

Trauma-Informed Safeguarding and Preview-Tour Audience Evaluation. Because *11th Quantum Dimension* engages domestic and intimate-partner violence, rehearsal and performance adhere to four mandatory safeguards: (1) explicit advance content advisories and unconditional opt-out agency for dancers and workshop learners to switch to abstract geometric framing without penalty; (2) certified trauma-informed movement and intimacy coordination governing all split-stage entanglement duets and physical boundary cues; (3) structured post-rehearsal somatic decompression cool-downs separating theatrical character states from personal identity; and (4) venue-specific domestic-abuse helpline resources displayed in printed programs and digital lobbies. Because $N = 0$ formal spectator surveys have been collected to date, live

preview-tour stagings will administer an opt-in 6-item post-show audience instrument pairing three 5-point somatic resonance items with three forced-choice conceptual decoding checks mapping Acts II–IV onto superposition, entanglement, and $\Delta\varphi = \pi$ interference.

6 Trapped-Ion Emulation, Stage Optimization, and Classical Flooring

To anchor the curriculum in verifiable quantum execution without hardware hype, we executed our choreographic circuits on the **Quantinuum Nexus `Helios-1E-lite`** noise-modeled trapped-ion emulator (`alpha` noise model, Guppy 1.0 → HUGR compilation with mid-circuit measurement and optical-pumping qubit reuse; 2,048 verified emulator shots across Jobs `d43f26d9-019d-4688-aa05-66c9cafe2f9b` and `a411dac7-1b75-4538-8ddc-16c560b30faa`; **0 physical QPU shots claimed**).

Table 6: 8-rung dynamic measurement ladder on Quantinuum Nexus `Helios-1E-lite` (Job UUID `d43f26d9-019d-4688-aa05-66c9cafe2f9b`; 1,024 shots/rung; `alpha` noise model).

#	Rung ID	Krump Choreographic Mapping	Target Δp	Ideal P_1	Shots (p_{raw})	Cal. Δp	Gate Status
1	`Cal_Std_1`	`LIVE` level (upward chest hit, $\theta_1 = 60.0°$)	−0.5000	0.2500	252/1024 (0.246)	−0.5040	**PASS** (0.004)
2	`Cal_Std_2`	`KRUMP` level (light sustained glide, $\theta_2 = 75.5°$)	−0.2500	0.3750	396/1024 (0.387)	−0.2165	**PASS** (0.034)
3	`Cal_Std_3`	Equatorial groove center ($\theta_3 = 90.0°$)	0.0000	0.5000	491/1024 (0.480)	−0.0268	**PASS** (0.027)
4	`Cal_Std_4`	`BUCK` level (sustained floor press, $\theta_4 = 104.5°$)	+0.2500	0.6250	614/1024 (0.600)	+0.2188	**PASS** (0.031)
5	`Cal_Std_5`	Deep `BUCK` ground slam ($\theta_5 = 120.0°$)	+0.5000	0.7500	769/1024 (0.751)	+0.5284	**PASS** (0.028)
6	`Blinded_QC`	Blinded quality-control holdout ($\theta_6 = 100.36°$)	+0.1800	0.5900	595/1024 (0.581)	+0.1809	**PASS** **[GA]** (0.0009)
7	`Choreo_K7`	`STOMP` → `CHEST POP` ($\theta_{\text{pop}} = 102.9°$)	+0.2240	0.6120	610/1024 (0.596)	+0.2109	**PASS** **[GC]** (0.0131)
8	`Null_Twin`	Exact-zero unperturbed control twin	0.0000	0.5000	511/1024 (0.499)	+0.0132	**PASS** **[GS]** (0.0132)

Table 7: Clifford-projected DisCoPy partner duet readout on `Helios-1E-lite` (Job UUID `a411dac7-1b75-4538-8ddc-16c560b30faa`; N = 1,024 emulator shots; 0 physical QPU shots claimed).

Basis State	Bitstring	Shots	Frequency	Choreographic & Physical Interpretation
$\|01\rangle$	`m0=0, m1=1`	**1,018**	**99.41%**	Target Bell-analyzer readout from $\|\Psi^+\rangle$ (5-stage Clifford projection with stage swap σ and cup ϵ_D).
$\|00\rangle, \|10\rangle, \|11\rangle$	Residual error states	1, 3, 2	0.59% total	Dephasing, single-qubit bit-flip, and 2-qubit readout infidelity under `alpha` noise model.

Emulator Verification and Multi-Dancer Stage Routing. Locked ordinary-least-squares affine calibration across Rungs 1–5 ($a = 0.4926 \pm 0.0076$, $b = 0.4891 \pm 0.0215$, $df = 3$, $R^2 = 0.9942$)

recovered the blinded QC target within $\Delta = 0.0009$, the analytic sagittal `STOMP` $\rightarrow$ `CHEST POP` reference angle ($\theta_{\text{pop}} = 102.9^\circ \implies \Delta p = -\cos\theta_{\text{pop}} = +0.2240$) within $\Delta = 0.0131$ ($\sigma_{\text{binom}} = 0.0153$), and exact-zero control within $|\Delta| = 0.0132$ (Table 6). In parallel, Job `a411dac7` executed a 5-stage Clifford stabilizer duet projection—Bell cap `h(q0); cx(q0,q1)`, local Clifford layer `h(q0); x(q1)`, routed `SWAP(q0,q1)`, inverse-compensating `ry(q0,pi/2); z(q0)`, and Bell analyzer `cx(q0,q1); h(q0)`—preparing $|\Psi^+\rangle \mapsto |01\rangle$ at 1,018/1,024 **shots (**99.41% **fidelity)** (connecting to stabilizer history decoding [35], whereas Figure 4b's uncompensated $Z \otimes X$ prefix prepares $-|\Psi^-\rangle \mapsto |11\rangle$ while leaving non-Clifford Layer 4 $R_x(\pi/2) \otimes R_z(\pi/2)$ out of the deterministic check). Noiseless classical statevector sampling in Rhyme (`rhyme-beta`) [36] confirmed 100% anti-phase extinction across 4,096 shots, and anisotropic Heisenberg Trotter evolution in HQS `struqture-py` [37] achieved $F = 0.9998$. For spatial staging on a 5×4 grid, multiplicity-normalized 5-qubit probabilities $\widetilde{P}(r, c)$ feed non-negative Dijkstra log-likelihood routing ($w(u, v) \geq 0$), Haiqu SDK 1.6.0+ state compression reduces 2-qubit gate depth by 85.7% ($84 \rightarrow 12$ layers, $F = 0.9996$) [38], and OpenJij simulated annealing (240 binary variables, 5,100 interactions; Gaussian stage-focus reward P_{focus} with $\lambda_{\text{one}} = 50, \lambda_{\text{col}} = 60$, Chebyshev King's-graph step penalty $\lambda_{\text{step}} = 40d_\infty$, and checkpoints at $t \in \{0, 2, 5\}$, omitting degree-4 HUBO edge-swap terms so partners pass laterally across $(2, 1) \leftrightarrow (2, 2)$) [39–41] schedules counter-diagonal trajectories in 1.63 s ($E_0 = -7.3569$) with 0 vertex collisions and 6/6 checkpoint hits.

Strict Classical Computational Floor and Automated Claim Linting. Evaluating Sandia's QUOPS volumetric metric [42, 43] on our 4-qubit, depth-32 emotion-wheel register yields $Q = 2wd_{\max} = 256$ ($\Omega_{\text{QPU}} \approx 44{,}444$ ops/s at $180\,\mu$s ion gate times), whereas exact classical CPU tensor contraction completes in $1.74\,\mu$s (3,310$\times$ faster throughput; 7,812.5$\times$ below $Q_{\text{utility}} = 2 \times 10^6$), and single-qubit Gate G4 evaluation takes $0.33\,\mu$s. Thus, classical computation strictly dominates all near-term choreographic circuits; quantum compilation serves structural isomorphism and QIS education rather than computational speedup. As an auxiliary prose-linting safeguard rather than independent mathematical proof, schema-constrained LLM checklist calls via TypeSafe Jev 1.14 (`jev-1.14.0`) [44] verified that manuscript claims explicitly disclose these classical floors and bounded metaphor rules.

7 Proficiency Rubric, Formative Insights, and Two-Phase Evaluation Design

Three-Tier Pathway, 10-Point Battle Rubric, and Cultural Respect. Learners progress across *Practitioner*, *Advanced Practitioner*, and *Trainer* tiers (the Trainer credential requiring multi-session co-facilitation apprenticeship). Closing studio battles are scored on a 10-point rubric: **Round 1** (Solo Superposition & Level Cleanliness, 3 pts), **Round 2** (Non-Visual Dyadic Entanglement across Z/X Bases, 3 pts), and **Round 3** (Collision-Free Swap & $\Delta\varphi = \pi$ Interference into Synchronized `KILL-OFF`, 4 pts). Facilitators explicitly distinguish the client-side educational badge "Quantum Krump #N" from earned cultural Krump *fam* ranks (*Baby*, *Lil*, *Kid*, *Young*, *Junior*, *Twin*) conferred solely through long-term mentorship under a *Big Homie* [8].

Formative Studio Co-Design Insights. Prior to formal psychometric trials, iterative studio prototyping during the Quantinuum Bradford Hackathon 2025 [15] and collaborative movement labs with street dancers from the Point Blank Fam and Easyar Dojo surfaced three concrete instructional refinements now embedded in the curriculum: (1) dancers without physics training grasped azimuthal phase φ significantly faster when anchored to the four quarter-note beats of a 145 BPM loop than via geometric radian angles alone; (2) explicitly naming the "classical lookup-table trap" before switching from Z-basis (`LIVE/BUCK`) to X-basis (`FORWARD/BACK`) partner calls prevented learners from conflating memorized unison choreography with quantum entanglement;

and (3) separating the percussive "HIT!" collapse cue in Phase 4 from the phrase-launching `STOMP` (H) in Phase 6 eliminated ambiguity around reversible versus projective operations.

Two-Phase Psychometric Calibration and Pre-Registered Randomized Trial. Because all results reported above constitute theoretical formalization, emulator verification, and formative co-design ($N = 0$ human-subjects efficacy claims to date), we decouple multilingual instrument calibration from causal intervention testing under IRB oversight and written informed consent:

- **Phase 1 — Multilingual QISCIT Calibration Pilot ($N \geq 90$):** Before intervention testing, the 12-item non-calculus subset of the validated *Quantum Information Science Concept Introductory Test (QISCIT)* [2] undergoes forward-backward translation and cognitive think-aloud validation across an independent sample of $N \geq 90$ learners ($n \geq 30$ per language in English, Hindi, and Tamil; plus French), requiring item discrimination $D_i \geq 0.20$ and Kuder–Richardson reliability KR-20 ≥ 0.70 prior to locking trial forms.
- **Phase 2 — Pre-Registered Two-Arm RCT ($N = 60$–100) & Power Analysis:** Physics-naive adult learners are randomized equally between the 75-minute embodied *Quantum Krump* studio curriculum and an active duration-matched interactive web-simulator control arm covering identical Bloch-sphere, Bell-state, and phase-interference syllabi without bodily movement. Under two-sided $\alpha = 0.05$ and $1 - \beta = 0.80$, $N = 60$ (30 per arm) detects individual-level standardized learning-gain effects of $d = 0.74$ on $g = (\text{post} - \text{pre})/(100 - \text{pre})$; accounting for studio-cohort clustering ($m = 10$ learners/session, intraclass correlation ICC $= 0.05$, design effect DEFF $= 1.45$) yields detectable effect sizes of $d_{\text{cluster}} = 0.89$ at $N = 60$ (6 clusters) and $d_{\text{cluster}} = 0.68$ at our target multi-site sample of $N = 100$ (10 clusters) across pre-, immediate post-, and 4-week retention endpoints.

8 Conclusion

Quantum Krump demonstrates that authentic urban street dance, structured by Laban Movement Analysis and formalized via dagger-compact monoidal string diagrams, offers an accessible, culturally grounded, and mathematically rigorous medium for QIS education and public theatrical storytelling. By pairing visceral somatic drills and trauma-informed dramaturgy with transparent classical computational baselines and a pre-registered randomized evaluation design, this work charts a principled path for embodied quantum literacy across classrooms, community studios, and international stages.

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AI Use Declaration

Large language models including Gemini 4 Argon, accessed within Google Antigravity, were used during this project to assist with verification scripts, simulation harnesses, manuscript editing, and adversarial review diagnostics. Throughout all stages, the authors directed the pedagogical and experimental design, verified every proposed equation, quantitative output, figure, and

bibliographic citation against primary sources and deterministic execution receipts, and take full responsibility for all analyses, claims, and content in this manuscript.

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