EDCA–Quantum Uncertainty: Emergence of a Measurement Tradeoff from Shell-Gated Collapse and Spin-Directed Selection

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Abstract

Energy-Driven Cellular Automata (EDCA) separate *logical readiness* from *physical transition*: a site may satisfy a local readiness condition yet remain unchanged until an energy quantum ("spot") arrives. Spots propagate as wavefronts and collapse only when intersecting transition-ready sites. When the wavefront intersects multiple ready sites, EDCA resolves ambiguity using an incidence principle driven by (i) wavefront geometry (privileged distance), (ii) a spot-attached spin vector that biases directional preference, and (iii) allocation density $\rho(x,t)$ of dynamically instantiated space. This paper explains, in EDCA-native terms, how an uncertainty-principle analog emerges from measurement itself. The key mechanism is that *distance and spin are complementary*: distance determines the privileged shell of candidates, while spin selects among candidates on that shell. We formalize measurement devices as engineered readiness/density masks and prove that there is an unavoidable tradeoff between localization of collapse position and the ability to infer the spot's "direction," understood operationally as its spin-induced bias among competing candidates. We provide quantitative scaling laws and an information-theoretic formulation: position uncertainty scales with the spatial extent of readiness support, direction uncertainty decreases with detector size and spin strength, yielding $\Delta x\,\Delta d \gtrsim 1/\beta$, and mutual information satisfies $I(X;S)=0$ for single-site gating while $I(X;S)>0$ for ring detectors under mild conditions. Although EDCA targets 3D physical reality, we use 2D figures for clarity; the arguments lift directly to 3D.

1 Introduction

Classical cellular automata update every cell synchronously at each tick. EDCA alter this causal structure: local rules define whether a site is *ready* to transition, but the transition occurs only if energy arrives. Readiness is necessary but not sufficient; physical change is event-driven by mobile energy quanta ("spots"). This separation yields a natural measurement-like architecture: wave-like energy propagation, discrete collapse events, and intrinsic back-action through polarity feedback [1].

In EDCA, a spot propagates outward as a wavefront. When the wavefront intersects one or more ready sites, it collapses onto a single site. The foundational EDCA formulation identifies three elements influencing collapse selection: distance from the spot source, a spin vector carried by the spot, and allocation density $\rho(x,t)$ in dynamically instantiated space [1]. Polarity feedback couples energy and matter: positive spots enable births and flip to negative; negative spots enable deaths and flip to positive [1].

This paper explains how an uncertainty-principle analog emerges in EDCA as a *measurement tradeoff*, without importing operator commutators. The core insight is that in a wavefront process, distance-to-source and spin are not competing forces. They are complementary:

- **Distance** determines the *privileged shell* (circle/sphere) of candidate sites at a given tick.
- **Spin** breaks symmetry and selects *which candidate on that shell* wins.

Because direction/spin information is expressed only through *comparative statistics among multiple candidates*, a measurement device that forces collapse at a single site destroys the degrees of freedom needed to infer direction. Conversely, a device that reveals direction must allow multiple candidates, which necessarily increases positional uncertainty.

2 EDCA Foundations and Notation

We adopt the notation and definitions of the EDCA foundational paper [1].

2.1 Lattice and fields

EDCA is defined on the cubic lattice $\mathbb{Z}^3$ with global time $t \in \mathbb{N}$ and spacing $a > 0$ [1]. For figures we often use a 2D slice for intuition; the wavefront becomes a circle rather than a sphere.

Matter field.

$$M_t : \mathbb{Z}^3 \to \{0, 1\},$$

where $M_t(x) = 1$ denotes a living cell at site x [1].

Energy field.

$$E_t : \mathbb{Z}^3 \to \{\emptyset, +, -\},$$

where $E_t(x) = +$ or $E_t(x) = -$ indicates a spot at site x, and $\emptyset$ indicates no spot [1].

2.2 Readiness predicates

Let $N(x)$ denote a neighborhood. EDCA defines readiness predicates:

$$R_t^+(x) = 1 \iff (M_t(x) = 0) \wedge B(M_t[N(x)]),$$

$$R_t^-(x) = 1 \iff (M_t(x) = 1) \wedge D(M_t[N(x)]),$$

where B and D define birth/death readiness. Readiness enables but does not force transitions [1].

2.3 Dynamic space and allocation density

EDCA can be implemented with dynamic instantiation. Let $A_t \subseteq \mathbb{Z}^3$ denote the instantiated set at time t. Define allocation density:

$$\rho(x, t) \in [0, 1],$$

which biases collapse toward denser allocated regions [1].

2.4 Polarity feedback

Upon collapse onto X, polarity determines interaction and then flips:

- $+$ at a birth-ready site triggers birth and flips to $-$,
- $-$ at a death-ready site triggers death and flips to $+$,

as described in [1]. This polarity flip is an intrinsic measurement back-action mechanism.

3 Shell-Gated Collapse and the EDCA Notion of Direction

3.1 Wavefront shell and shell thickness

Consider a spot emitted from a source x_s at time t_s. At tick t, the spot wavefront is approximately a spherical shell of radius

$$r(t) \approx c(t - t_s),$$

for some propagation speed $c > 0$ [1]. In a 2D slice, this is a circular ring.

Define the wavefront shell band:

$$W_t \; = \; \{x \in \mathbb{Z}^3 : \; \|x - x_s\| \in [r(t) - \delta_r, \; r(t) + \delta_r]\}, \tag{1}$$

where δ_r is the effective shell thickness.

Role of λ. The foundational distance-sensitivity parameter λ controls radial localization: larger λ corresponds to a thinner effective shell (smaller δ_r), producing more sharply localized collapse in radius [1]. In this paper, λ is interpreted primarily as a *shell-thickness / radial gating* parameter.

3.2 Candidate set = (shell) ∩ (readiness)

At tick t, define the candidate set:

$$C_t = W_t \cap \{x : \; R_t^+(x) = 1 \text{ or } R_t^-(x) = 1\}. \tag{2}$$

If $C_t = \emptyset$, propagation continues; if $C_t \neq \emptyset$, collapse occurs onto one site $X \in C_t$ [1].

3.3 Local outward direction and spot spin

Even for spherical wavefronts, each point has a local outward direction:

$$d(x) = \frac{x - x_s}{\|x - x_s\|} \quad (x \neq x_s). \tag{3}$$

Each spot carries a fixed unit spin vector:

$$s \in \mathbb{R}^3, \qquad \|s\| = 1,$$

attached to the spot (not to cells). Spin influences selection among candidates on the same shell.

Define alignment:

$$\chi(x) = s \cdot d(x) \in [-1, 1]. \tag{4}$$

Operational direction in EDCA. Direction is not a particle velocity; it is the spot's spin-induced preference among competing candidates on a shell. Measuring direction means extracting information about s from collapse outcomes.

4 Shell-Conditioned Collapse Model (Distance as Gate, Spin as Selector)

Because $C_t \subseteq W_t$, candidates lie on the same privileged-distance shell (to within shell thickness). Therefore, within a fixed collapse event, distance-to-source does not meaningfully distinguish candidates—distance has already performed its role by defining the shell. Selection occurs among candidates *conditioned on the shell.*

4.1 Shell-conditioned preference scores

For $x \in C_t$, define the shell-conditioned preference score:

$$S_{t,\pm}(x) = \rho(x,t)^{\gamma}\, A_t(x)\, \exp\big(\pm\beta(s\cdot d(x))\big), \tag{5}$$

where:

- $\gamma > 0$ controls density preference [1],
- $A_t(x) \geq 0$ is an optional amplitude/intensity factor (useful for later interference modeling but not required for uncertainty),
- $\beta \geq 0$ controls the strength of spin selection,
- the sign depends on spot polarity (+ prefers alignment; − prefers anti-alignment).

4.2 Shell-conditioned collapse probability

Given $C_t \neq \emptyset$, collapse is sampled as:

$$\mathbb{P}(X = x \mid C_t, \pm) = \frac{S_{t,\pm}(x)}{\sum_{z\in C_t} S_{t,\pm}(z)}. \tag{6}$$

5 Measurement Devices as Readiness/Density Masks

In EDCA, a measurement device is modeled as a physical configuration that shapes readiness and density, i.e., it determines which candidates exist.

We analyze two canonical devices.

5.1 Device P: Single-site readiness gate (position measurement)

Fix a single site $x_0 \in \mathbb{Z}^3$. Engineer readiness such that when the wavefront reaches the detector:

$$C_t = \{x_0\}.$$

Collapse is forced at one location.

5.2 Device R: Ring/shell detector (direction/spin measurement)

Fix a detector center x_d and radius R. Define:

$$\mathcal{R} = \{x : \ \|x - x_d\| \in [R - \tfrac{1}{2},\ R + \tfrac{1}{2}]\}.$$

Engineer readiness such that:

$$C_t = \mathcal{R} \cap W_t.$$

This creates many candidates spanning many directions.

6 Position Uncertainty Measures

Let X be the collapse site.

6.1 Entropy-based position uncertainty

$$H(X) = -\sum_{x\in C_t} \mathbb{P}(X = x) \log \mathbb{P}(X = x). \tag{7}$$

6.2 Geometry-based position uncertainty

If a coordinate embedding is used, one may define Δx as the standard deviation of collapse coordinates. In the ring detector case, the characteristic positional scale is R.

7 Theorem: Shell-Based EDCA Uncertainty Tradeoff

Theorem 7.1 (Shell-Conditioned EDCA Uncertainty Tradeoff)**.** *Let a spot emitted at x_s define a wavefront shell band W_t as in* (1)*. Let*

$$C_t = W_t \cap \{x : \; R_t^+(x) = 1 \text{ or } R_t^-(x) = 1\}$$

be the candidate set at collapse time, and assume shell-conditioned collapse sampling (6) *with scores* (5)*, with $\beta > 0$ and nonnegative factors.*

1. ***Single-site readiness implies perfect localization and zero spin information.*** *If readiness is engineered so that $C_t = \{x_0\}$, then:*

   $$\mathbb{P}(X = x_0) = 1, \qquad H(X) = 0,$$

   and the outcome distribution is independent of the spin vector s. Hence no direction/spin information is extractable.

2. ***Distributed shell/ring readiness implies spin observability and nonzero position uncertainty.*** *If readiness is engineered such that C_t contains at least two sites x, y with different outward directions $d(x) \neq d(y)$ and such that their scores are not identically zero, then the collapse distribution depends on s (direction/spin is observable), and $H(X) > 0$ (position uncertainty is nonzero). In the ring detector case, $\Delta x \sim R$.*

Proof. **(1) Single-site gate.** If $C_t = \{x_0\}$, then $\mathbb{P}(X = x_0 \mid C_t) = 1$ by normalization, so X is deterministic and $H(X) = 0$. Since this holds for any spin s, the distribution is independent of s.

(2) Distributed shell/ring detector. If C_t contains at least two candidates with distinct outward directions, then varying s changes relative weights $\exp(\pm\beta(s \cdot d(x)))$ across candidates when $\beta > 0$, making $\mathbb{P}(X = \cdot \mid s)$ spin-dependent. Because $|C_t| > 1$ with nonzero scores, X is non-deterministic and $H(X) > 0$. In the ring/shell case, the region of support has scale R, so $\Delta x \sim R$. □

8 Direction Uncertainty, Formal Δd, and Quantitative Scaling

8.1 Detector-defined direction observable

Under Device R, define:

$$u(x) = \frac{x - x_d}{\|x - x_d\|} \in \mathbb{S}^2, \qquad U = u(X).$$

8.2 Formal definitions of direction uncertainty Δd

8.2.1 Angular-entropy direction uncertainty

Partition the unit circle/sphere into K bins $\{B_1, \ldots, B_K\}$. Define

$$\tilde{U} = k \quad \text{iff} \quad U \in B_k,$$

and set:

$$\Delta d \equiv H(\tilde{U}) = -\sum_{k=1}^{K} \mathbb{P}(\tilde{U} = k) \log \mathbb{P}(\tilde{U} = k). \tag{8}$$

8.2.2 Dispersion (mean resultant) direction uncertainty

Define:

$$\mu = \mathbb{E}[U] = \sum_{x \in C_t} u(x)\, \mathbb{P}(X = x), \qquad \Delta d \equiv 1 - \|\mu\|.$$

8.3 Position scaling

For a ring/shell detector of radius R, collapse is distributed over a region of scale R, giving:

$$\Delta x \sim R.$$

8.4 Direction scaling and the role of β and R

In an idealized regime where $\rho(x,t)^\gamma A_t(x)$ is approximately constant over the ring/shell,

$$\mathbb{P}(X = x) \propto \exp\big(\beta(s \cdot d(x))\big)$$

(for positive polarity; negative polarity flips sign). A larger ring provides finer angular discretization (more distinct directions), and larger β increases concentration around the favored direction. A minimal scaling consistent with both effects is:

$$\Delta d \sim \frac{1}{\beta R}.$$

8.5 EDCA uncertainty relation (scaling form)

With $\Delta x \sim R$ and $\Delta d \sim 1/(\beta R)$, we obtain:

$$\Delta x\, \Delta d \gtrsim \frac{1}{\beta}.$$

In this shell-conditioned interpretation, λ regulates radial localization by controlling shell thickness δ_r while spin remains the selector within the shell [1].

9 Information-Theoretic Formulation: Mutual Information Between Collapse Outcomes and Spin

The uncertainty tradeoff can be expressed as an information constraint: precise localization eliminates the statistical degrees of freedom needed to infer spin/direction.

9.1 Spin as a random variable

Let S be a random variable representing spot spin, taking values in a finite set $\{s^{(1)}, \ldots, s^{(m)}\} \subset \mathbb{S}^2$ with prior $\mathbb{P}(S = s^{(i)})$. Let X be the collapse outcome. Mutual information

$$I(X; S)$$

quantifies how much observing X reveals about S.

9.2 Corollary: single-site gate yields $I(X;S) = 0$; ring yields $I(X;S) > 0$

Corollary 9.1 (Mutual Information: Single-Site Gate vs Ring Detector)**.** *Assume shell-conditioned collapse sampling:*

$$\mathbb{P}(X = x \mid C_t, S = s) \propto \rho(x,t)^\gamma A_t(x) \exp(\pm\beta(s \cdot d(x))),$$

with $\beta > 0$*.*

1. *If readiness is engineered such that* $C_t = \{x_0\}$*, then* $I(X;S) = 0$*.*
2. *If readiness is engineered such that* C_t *contains at least two candidates* x, y *with distinct directions* $d(x) \neq d(y)$*, and if* $\rho(x,t)^\gamma A_t(x)$ *does not cancel the spin dependence identically, then* $I(X;S) > 0$*.*

Proof. (1) If $C_t = \{x_0\}$, then $X = x_0$ almost surely regardless of S; therefore $\mathbb{P}(X \mid S)$ is independent of S, giving $I(X;S) = 0$.

(2) With at least two candidates of distinct direction and $\beta > 0$, there exist $s^{(i)} \neq s^{(j)}$ such that:

$$\mathbb{P}(X = \cdot \mid S = s^{(i)}) \neq \mathbb{P}(X = \cdot \mid S = s^{(j)}),$$

because $\exp(\pm\beta(s \cdot d(x)))$ changes relative weights across candidates. When conditional distributions differ for at least two values of S, mutual information is strictly positive. □

9.3 Polarity-flip back-action and measurement disturbance

Polarity feedback reverses the sign of the spin preference between successive collapse events:

$$\exp(+\beta(s \cdot d)) \longleftrightarrow \exp(-\beta(s \cdot d)).$$

Therefore repeated measurement is not passive: each detection event injects a subsequent influence with inverted directional preference, ensuring an EDCA-native measurement disturbance mechanism consistent with the uncertainty tradeoff [1].

10 Figures: 2D Intuition for 3D EDCA

Although EDCA targets a 3D substrate, the measurement tradeoff is easiest to visualize in 2D. The figures below depict a 2D slice: wavefronts become circles and detectors become points or rings. All arguments lift directly to 3D by replacing circles with spheres and ring detectors with spherical shells.

10.1 2D grid snapshot: wavefront intersecting readiness nodes

10.2 Device P: single-site readiness gate

10.3 Device R: ring/shell detector

10.4 Polarity and hit distributions (schematic)

11 Discussion

This framework differs from standard quantum mechanics in origin: uncertainty emerges not from operator algebra but from EDCA's measurement architecture.

1. **Readiness-gated collapse** means measurement is the act of shaping which sites can collapse.

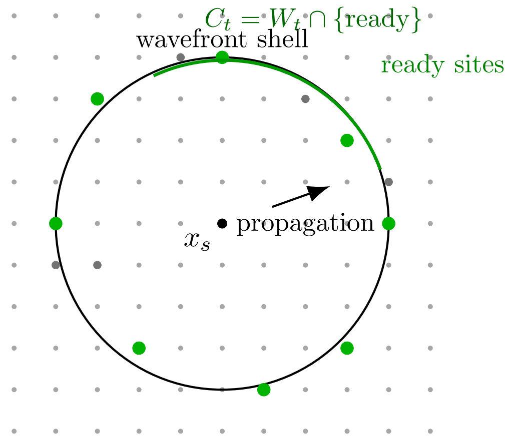

Figure 1: 2D grid snapshot (for intuition). A spot emitted at x_s expands as a wavefront shell (circle). Readiness highlights which sites are eligible for collapse. The candidate set C_t is the intersection of the shell with ready sites. When C_t has multiple elements, spin and density bias selection among them.

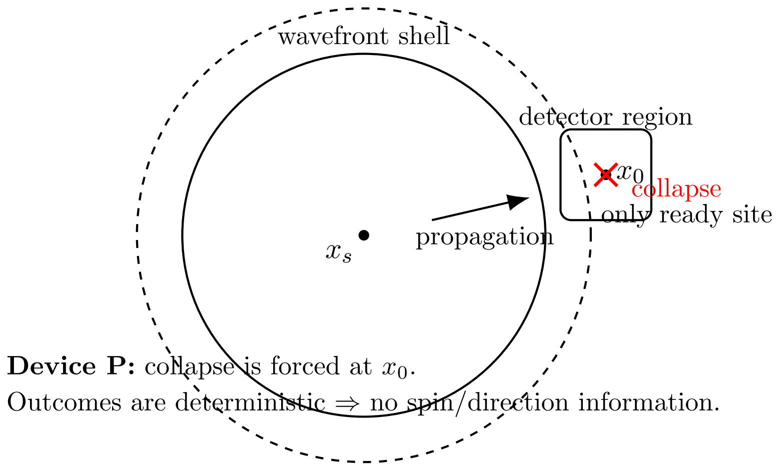

Figure 2: Single-site readiness gate (Device P). If only one site x_0 is ready on the shell, collapse is forced at x_0 (perfect localization). With no competing candidates, the outcome is independent of spin: direction cannot be inferred.

2. **Shell gating** ensures distance and spin are complementary: distance defines the eligible shell; spin breaks symmetry within the shell.
3. **Spin is observable only through multi-candidate statistics**, which disappear under perfect localization.
4. **Polarity flip** produces intrinsic back-action that alters future directional tendencies [1].
5. **Allocation density** $\rho(x,t)$ allows detectors to further bias collapse selection by structuring the dynamically instantiated medium [1].

This yields a clear EDCA-native analog of complementarity: sharp position measurement and sharp direction inference are structurally incompatible because they require incompatible readiness configurations.

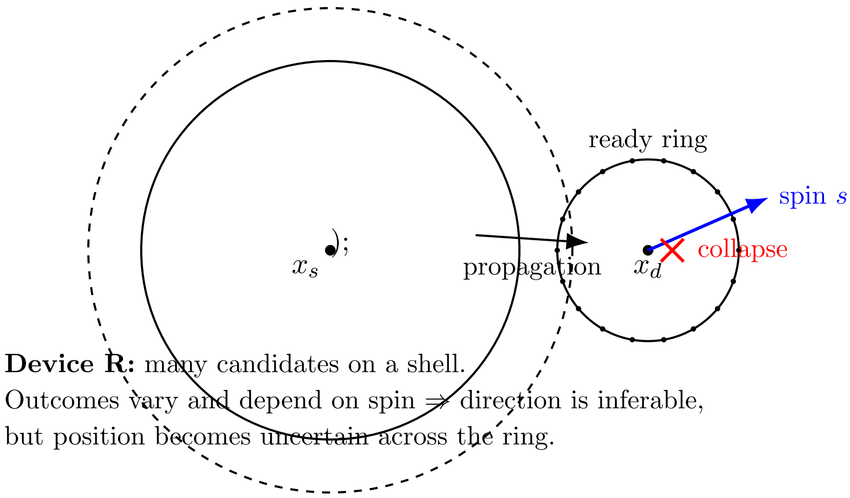

Figure 3: Ring/shell detector (Device R). The wavefront reaches a ready ring with many candidates. Collapse occurs at one site, but the distribution of outcomes is biased by spot spin s (for $+$ polarity; for $-$ polarity the bias reverses). This yields direction information at the cost of increased position uncertainty.

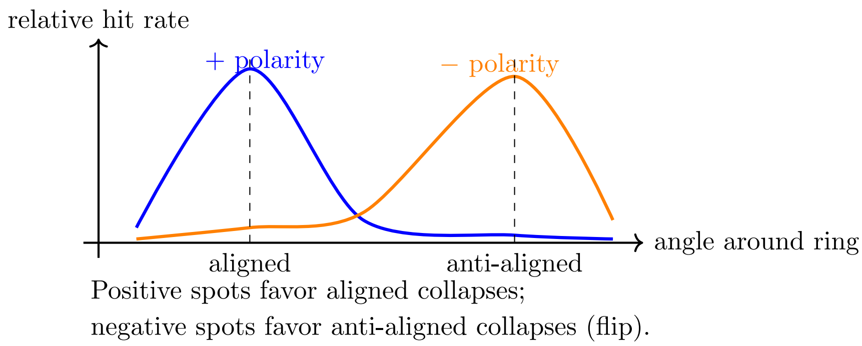

Figure 4: Schematic ring hit distributions. For positive polarity, collapse is biased toward alignment with the spin direction; for negative polarity, the bias reverses. This polarity flip acts as intrinsic back-action and reinforces the measurement tradeoff.

12 Conclusion

We presented a shell-conditioned EDCA measurement model that formalizes the complementarity between distance and spin: distance determines the wavefront shell of candidates and spin selects among candidates within that shell. We proved that perfect position localization (single-site readiness gating) yields deterministic collapse but eliminates direction/spin information, while distributed ring/shell readiness enables direction/spin inference at the cost of increased positional uncertainty. We formalized direction uncertainty Δd and provided both a scaling relation $\Delta x\,\Delta d \gtrsim 1/\beta$ and an information-theoretic corollary. The distance-sensitivity parameter λ is interpreted as controlling shell thickness and radial localization, without competing with spin within the shell. This explains uncertainty-like behavior as an emergent measurement tradeoff inherent to EDCA's readiness-gated collapse and spin-directed selection.

References

[1] Raul Sanchez Perez. *Energy-Driven Cellular Automata (EDCA): Foundational Definition, Dynamic Space, and Conservative Properties.* EDCAWorld, Jan 2026. Available at: `https:`

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