Energy-Driven Cellular Automata (EDCA): Foundational Definition, Dynamic Space, and Conservative Properties

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Abstract

Energy-Driven Cellular Automata (EDCA) are cellular automata in which local state transitions are explicitly gated by the arrival of discrete energy quanta. Matter is represented by persistent living cells, while energy is represented by mobile spots that propagate as wavefronts and collapse to enable transitions. Unlike classical cellular automata, EDCA separate global computational time from local state change: a cell may be logically ready to transition yet remain unchanged until energy arrives. This paper presents a readable foundational definition of EDCA on a three-dimensional lattice with dynamically instantiated space, together with polarity feedback between matter and energy. We derive strict and asymptotic conservative properties linking matter and energy, and we provide a precise formal definition of the energy incidence criterion in an appendix.

Contents

1 Introduction

Classical cellular automata update all cells synchronously at each tick. While this assumption simplifies analysis, it hides an important distinction: in many systems, time may pass without change, and change requires enabling interactions.

Energy-Driven Cellular Automata (EDCA) make this distinction explicit. Local rules no longer force transitions; instead, they define *readiness*. A transition occurs only when energy reaches a ready site. This introduces explicit propagation of energy, local causal ordering, feedback between creation and destruction, and the possibility of emergent spatial structure.

This paper provides a foundational EDCA definition intended to be conceptually clear and operationally precise.

2 EDCA Ontology and Configuration

2.1 Matter and energy

An EDCA consists of two interacting components:

- **Matter**: persistent living cells located at lattice sites.
- **Energy**: mobile discrete quanta called *spots*, which enable transitions.

Matter does not propagate. Energy does.

2.2 Lattice and fields

We consider a three-dimensional cubic lattice

$$\mathbb{Z}^3$$

with lattice spacing $a > 0$. At each global tick $t \in \mathbb{N}$, the configuration consists of:

Matter field

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

where $M_t(x) = 1$ denotes a living cell and $M_t(x) = 0$ denotes absence of matter.

Energy field

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

where $+$ and $-$ denote positive and negative energy spots, and $\varnothing$ denotes no spot.

Remark 2.1. For compatibility with formal EDCA descriptions, the energy field may equivalently be represented as $E_t(x) \in \{-1, 0, +1\}$.

3 Readiness: Local Rules Without Forced Updates

Let $N(x)$ denote a finite neighborhood of site x. The neighborhood matter configuration is

$$M_t[N(x)] = \{M_t(y) : y \in N(x)\}.$$

EDCA defines two readiness predicates:

Birth readiness

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

where B is a local birth condition.

Death readiness

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

where D is a local death condition.

Remark 3.1. Readiness does not imply transition. A site may remain ready for birth or death indefinitely if no energy arrives.

4 Energy Spots and Wavefront Propagation

4.1 Propagation

Each energy spot is emitted at time t_0 from a source site $x_0 \in \mathbb{Z}^3$ and propagates isotropically as a wavefront.

At time $t \geq t_0$, the wavefront radius is approximately

$$r(t) \approx c(t - t_0),$$

where $c > 0$ is an effective propagation speed in lattice units per tick.

4.2 Candidate sites and collapse

At each tick, the wavefront may intersect transition-ready sites. Define

$$C_t = \{x \text{ on the wavefront at time } t : R_t^+(x) = 1 \text{ or } R_t^-(x) = 1\}.$$

- If $C_t = \varnothing$, the wavefront continues propagating.
- If $C_t \neq \varnothing$, the wavefront collapses onto one site selected by an incidence criterion.

5 Energy–Matter Interaction and Polarity Feedback

When a spot collapses onto a site X, interaction occurs according to polarity:

Positive spot If $E_t(X) = +$ and $R_t^+(X) = 1$, then

$$M_{t+1}(X) = 1, \qquad E_{t+1}(X) = -.$$

Negative spot If $E_t(X) = -$ and $R_t^-(X) = 1$, then

$$M_{t+1}(X) = 0, \qquad E_{t+1}(X) = +.$$

Otherwise If polarity does not match readiness, no transition occurs and the wavefront continues.

Remark 5.1. Birth flips $+ \to -$ and death flips $- \to +$. This polarity feedback couples creation and destruction.

6 Dynamic Space and Allocation Density

6.1 Dynamic instantiation

EDCA may be implemented on a dynamically instantiated lattice. A site is instantiated when it:

- becomes living,
- is reached by a wavefront,
- or is needed to evaluate a neighborhood.

Let $A_t \subset \mathbb{Z}^3$ be the set of instantiated sites at time t.

6.2 Allocation density

Define a coarse-grained allocation density

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

measuring how densely instantiated the neighborhood of x is.

Priority principle When conflicts arise, spots preferentially collapse onto sites with higher allocation density. Already-instantiated space has priority.

7 Energy Incidence Criterion (Narrative)

When a wavefront intersects multiple ready sites, EDCA resolves the conflict using three influences:

1. **Distance from source**: closer or earlier-reached sites are favored.
2. **Spin vector**: each spot carries an internal direction bias.
3. **Allocation density**: higher ρ increases priority.

7.1 Incidence parameters and their interpretation

The energy incidence criterion combines several influences into a single preference score. This construction introduces two parameters, λ and γ, which control the relative importance of different selection mechanisms. These parameters are not universal constants; they are part of the EDCA model specification and determine how energy interacts with matter and space.

Distance sensitivity parameter λ. The parameter $\lambda > 0$ controls how strongly the collapse of a wavefront is biased toward sites that are closer to the spot's source. Large values of λ make collapse highly local: among competing candidates, the closest sites are strongly preferred. Small values of λ weaken the role of distance, allowing other factors such as spin alignment or allocation density to dominate.

Operationally, λ sets an effective interaction length scale for energy spots. It determines how sharply causal proximity constrains energy–matter interaction.

Allocation-density bias exponent γ. The parameter $\gamma > 0$ controls how strongly already-instantiated space is preferred during collapse. When $\gamma = 1$, allocation density influences collapse linearly. Values $\gamma > 1$ amplify this effect, producing a strong preference for highly instantiated regions. Values $0 < \gamma < 1$ correspond to a weaker bias, where low- and high-density regions are treated more evenly.

The exponent γ therefore controls how strongly spatial structure reinforces itself through repeated activity.

Each spot may collapse at most once per tick. A precise formal definition is given in Appendix A.

8 Conservative Properties

8.1 Spot count

Let K be the number of spots.

Lemma 8.1. *The number of spots is conserved.*

Proof. Spots propagate and collapse but are neither created nor destroyed. Only polarity changes. □

8.2 Matter–energy invariant

Define the total matter content

$$\sigma_t = \sum_{x \in \mathbb{Z}^3} M_t(x),$$

assuming finite support.

Define the algebraic energy

$$E_t = \sum_{k=1}^{K} v_t(k),$$

where $v_t(k) \in \{-1, +1\}$ is the polarity of spot k.

Theorem 8.1. *The quantity*

$$2\sigma_t + E_t$$

is invariant in time.

Proof. A birth increases σ by 1 and flips a $+$ spot to $-$, decreasing E by 2. A death decreases σ by 1 and flips a $-$ spot to $+$, increasing E by 2. In both cases, $2\sigma + E$ remains unchanged. □

8.3 Asymptotic conservation of average matter

Define the time average

$$\bar{\sigma}(t) = \frac{1}{t} \sum_{\tau=0}^{t} \sigma_\tau.$$

Theorem 8.2. *The average matter content converges asymptotically:*

$$\lim_{t \to \infty} \bar{\sigma}(t) = \sigma_0 + \frac{E_0}{2}.$$

Proof. From the invariant $2\sigma_t + E_t = 2\sigma_0 + E_0$, we obtain

$$\sigma_t = \sigma_0 + \frac{E_0}{2} - \frac{E_t}{2}.$$

Since E_t is bounded ($|E_t| \le K$), the average contribution of E_t vanishes as $t \to \infty$, yielding the result. □

9 Conclusion

EDCA extend cellular automata by making state change explicitly dependent on energy arrival. By separating readiness from transition, introducing propagating energy spots, and allowing space to be dynamically instantiated, EDCA provide a causal and conservative framework for interaction-driven dynamics.

A Formal Definition of the Incidence Criterion

A.1 Spot data

Each spot k has:

- source position $x_k \in \mathbb{Z}^3$,
- emission time $t_0(k)$,
- polarity $v_t(k) \in \{-1, +1\}$,
- spin vector $\vec{s}(k) \in \mathbb{R}^3$, $\|\vec{s}(k)\| = 1$.

A.2 Candidate set

At time t,

$$C_t(k) = \begin{cases} \{x : \|x - x_k\| \approx r_k(t),\ R_t^+(x) = 1\}, & v_t(k) = +1, \\ \{x : \|x - x_k\| \approx r_k(t),\ R_t^-(x) = 1\}, & v_t(k) = -1. \end{cases}$$

A.3 Preference score

The parameters λ and γ are model parameters introduced in Section 7.1; they respectively control the strength of distance-based selection and the priority given to already-instantiated space.

The incidence criterion ranks candidates using a preference score composed of three independent weights.

Distance weight

$$w_d(k, x) = \exp(-\lambda \|x - x_k\|), \qquad \lambda > 0.$$

Spin alignment

$$w_s(k, x) = \frac{1 + \vec{s}(k) \cdot \frac{x - x_k}{\|x - x_k\|}}{2}.$$

Allocation density weight

$$w_\rho(x, t) = \rho(x, t)^\gamma, \qquad \gamma > 0.$$

Composite score

$$W_t(k, x) = w_d(k, x)\, w_s(k, x)\, w_\rho(x, t).$$

A.4 Collapse rule

If $C_t(k) \neq \varnothing$, the collapse target is

$$X = \arg \max_{x \in C_t(k)} W_t(k, x),$$

with deterministic or probabilistic tie-breaking.

References

[1] R. Sanchez Perez, *Formal Description of Energy-Driven Cellular Automata*, EDCAWorld Technical Note, 2018. https://edcaworld.com/wp-content/uploads/2018/02/formal.pdf

[2] R. Sanchez Perez, *Additive and Asymptotically Conserved Quantities in EDCA*, EDCAWorld Technical Note, 2018. https://edcaworld.com/wp-content/uploads/2018/01/conservation2.pdf