Numerical Analysis Final Project
Simulation of Lightning Fractal Structure

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1 Motivations

Lightning displays complex branching patterns, which are visually striking and scientifically intriguing. This study explores:

- How are lightning branch shapes formed?
- Can similar structures be simulated using programming?
- What factors influence the appearance and formation of these patterns?

Air impurities and moisture cause ionization in various directions, and lightning channels follow paths of least resistance. These physical factors create a highly intricate phenomenon that motivates the use of computational models to replicate and analyze its properties. By leveraging simplified models, we aim to deepen our understanding of fractal geometry and its applications in simulating natural phenomena.

2 Methods

Fractal geometry serves as the foundation to simulate lightning's branching structure due to its iterative and self-similar properties. Two primary approaches were employed: the Diffusion-Limited Aggregation (DLA) model and the Lindenmayer System (L-System) model.

2.1 Diffusion-Limited Aggregation (DLA) Model

The DLA model mimics particle aggregation processes observed in nature:

- Particles perform random walks until they collide and stick to an existing cluster.
- Produces fractal structures with stable fractal dimensions.
- Captures the out-of-equilibrium dynamics of growth processes.

Steps to simulate:

1. Place a nucleus at the origin.
2. Generate a new particle randomly and allow it to perform a random walk.
3. When the particle touches the existing cluster, it adheres to it.
4. Repeat until a complete structure is formed.

Additional modifications include applying an external electric field to influence particle motion, enhancing the resemblance to natural lightning.

2.2 Lindenmayer System (L-System) Model

L-systems use recursive rules to generate self-similar structures, often applied in modeling plant growth but adaptable to simulate lightning patterns.

Key features include:

- Recursive application of rules to generate complex geometries.
- Control over branching probabilities and angles for realistic patterns.
- Integration of randomization for enhanced natural variability.

Steps to simulate:

1. Define an initial string and interpretation rules.
2. Recursively apply the rules to generate iterations.
3. Adjust branch thickness, length, and probabilities during optimization.
4. Differentiate between main trunks and secondary branches for enhanced visual realism.

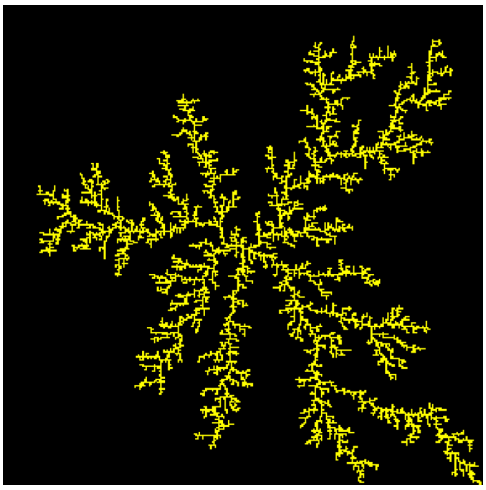

Fig 1. DLA model simulation result

- Introducing an electric field in the DLA model directs particle growth downward, enhancing resemblance to lightning.

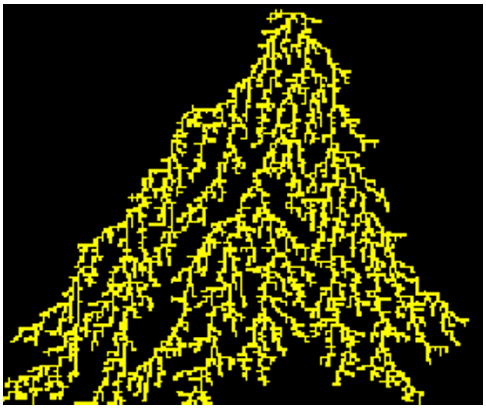

Fig 2. DLA model simulation result (add electric field)

3 Results

Simulated results using the DLA and L-System models effectively mimic lightning fractal structures. Key observations include:

- The DLA model generates irregular, branching patterns resembling natural discharges.
- The L-System model creates visually striking, organized fractal patterns with adjustable complexity.

Fig 3. L-System model simulation result

4 verification tests

To validate the accuracy and realism of the simulations:

- Visual comparison of simulated results against real lightning patterns was conducted, highlighting structural similarities.
- Fractal dimensions were calculated and compared to known values of natural lightning, confirming scaling consistency.
- Sensitivity tests evaluated the impact of parameters like step size, branching probability, and recursion depth.

5 discussions & conclusions

This project demonstrated that fractal models, such as the DLA and L-System, can successfully simulate lightning's branching structure. Simplified algorithms proved effective in mimicking the visual complexity of natural systems. Future work could focus on:

- Exploring hybrid models that integrate DLA and L-System features.
- Incorporating more sophisticated physical dynamics, such as charge accumulation and discharge mechanisms.
- Extending the approach to simulate other fractal phenomena in nature.

The study highlights the power of computational techniques in unraveling the intricacies of natural phenomena and provides a foundation for further exploration in this fascinating domain.

References

[1] Python Simulation of Lightning Formation (DLA Model) `https://www.bilibili.com/video/BV1P54y1X75o/`

[2] Lindenmayer System Fractal Graphics - A Lightning Example `https://tedsieblog.wordpress.com/2020/04/16/lindenmayer-system-a-case-study\-of-lightning-bolts/`