Perceiving without learning: from spirals to inside/outside relations

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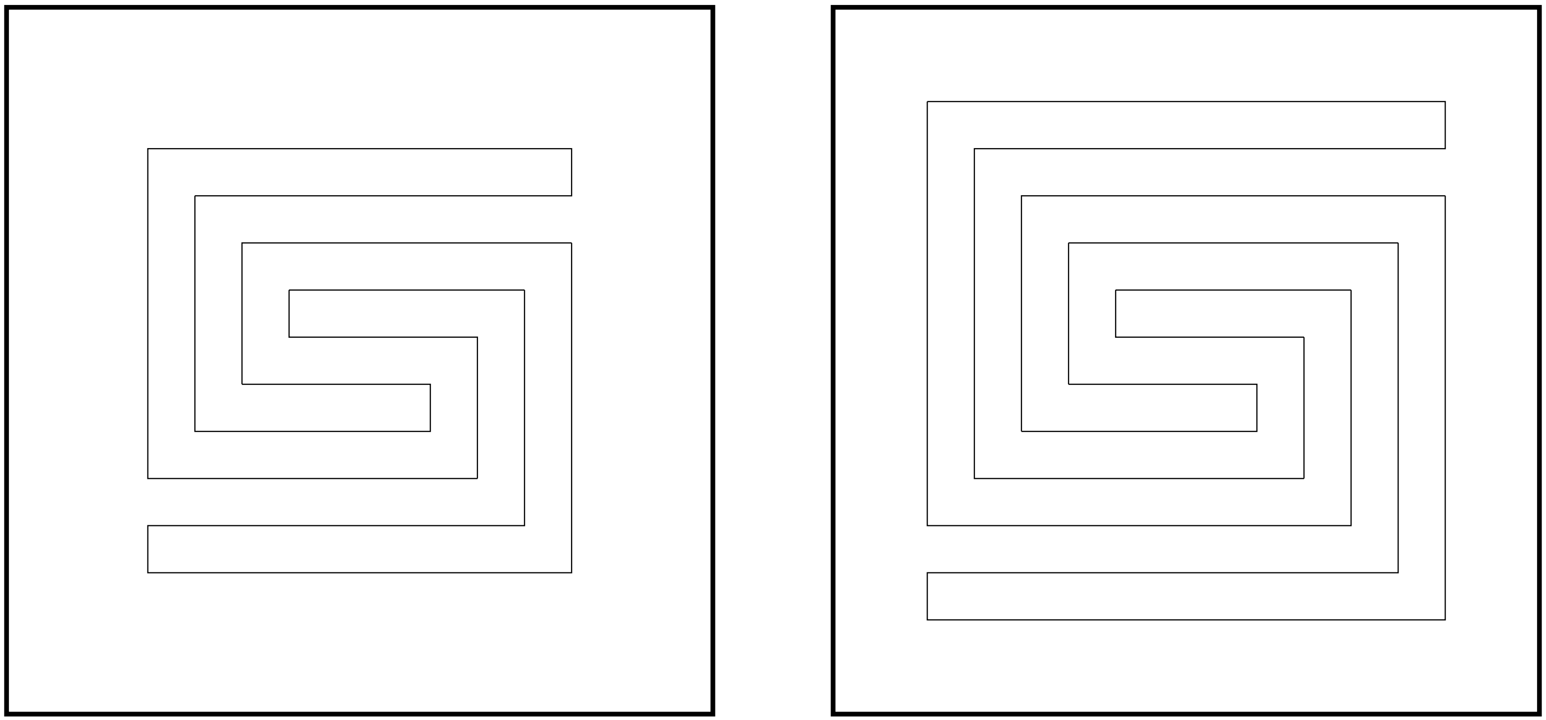
Abstract

As a benchmark task, the spiral problem is well known in neural networks. Unlike previous work that emphasizes learning, we approach the problem from a generic perspective that does not involve learning. We point out that the spiral problem is intrinsically related to the inside/outside problem. A solution to both problems is proposed based on oscillatory correlation using a time delay network. Our simulation results are qualitatively consistent with human performance, and we interpret human limitations in terms of synchrony and time delays, both biologically plausible. As a special case, our network without time delays can always distinguish these figures regardless of shape, position, size, and orientation. We conjecture that visual perception will be effortful if local activation cannot be rapidly propagated, as synchrony would not be established in the presence of time delays.

Background

- The Spiral Problem (Minsky & Papert, 1969)

  Distinguish between a connected single spiral and disconnected double spirals on a two-dimensional plane.

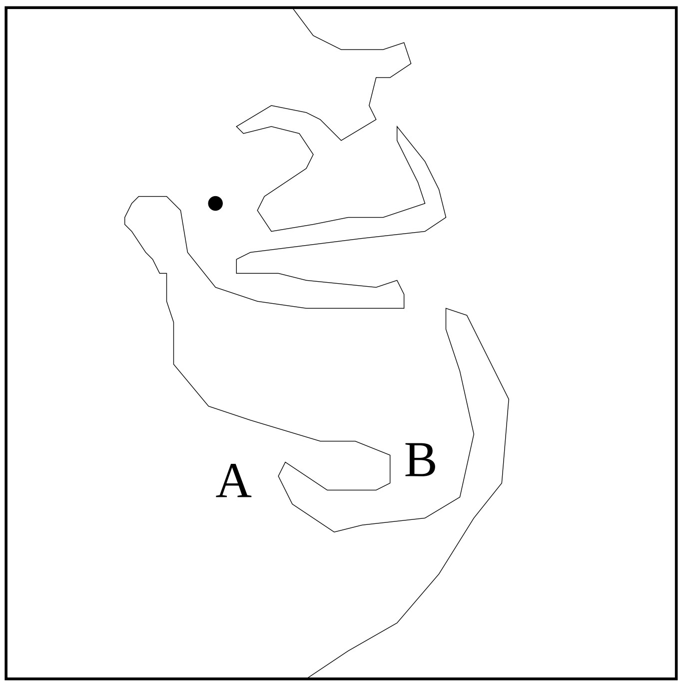


(Adapted from Minsky and Papert, 1969)

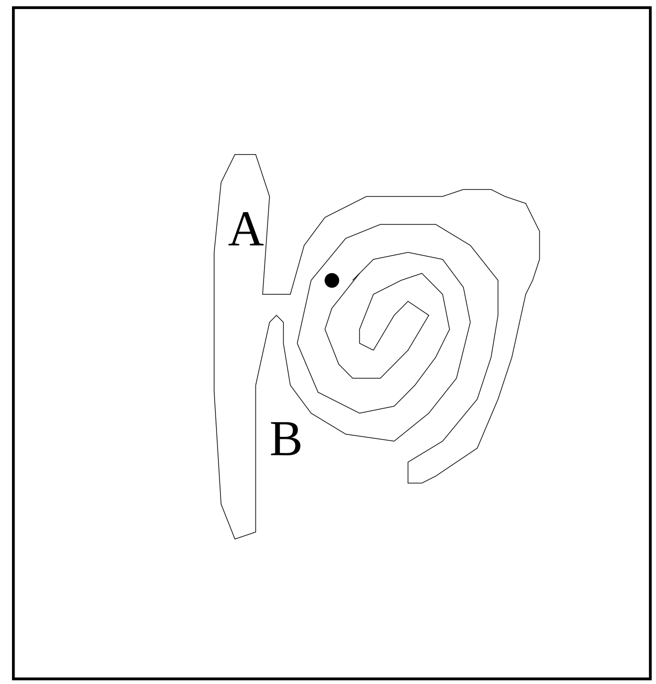
Background

- Inside/Outside Relations (Ullman, 1984)

  For a single closed curve, determine whether a dot lies inside or outside the closed curve.



(Adapted from Julesz, 1995)



(Adapted from Ullman, 1984)

Background

- Earlier Studies: The Spiral Problem
  - A benchmark problem in neural networks (Fahlman, 1993)
  - Grossberg and Wyse (1991) using interacting BCS and FCS systems, with limited success
  - The problem in the general form remains open for neural networks.
- Earlier Studies: Inside/Outside Relations
  - Visual routine theory (Ullman, 1984): creation of representation and application of visual routines
  - The neural processes underlying inside/outside relations are as yet unknown (Ullman, 1996).

Objectives

- Attempt to address the following questions:
  - Why humans cannot immediately distinguish between connected and disconnected spirals?
  - What is a relation between the spiral problem and the inside/outside relations?
  - How to perceive the inside/outside relations in neural networks?
- Propose a generic solution to both problems based on oscillatory correlation.

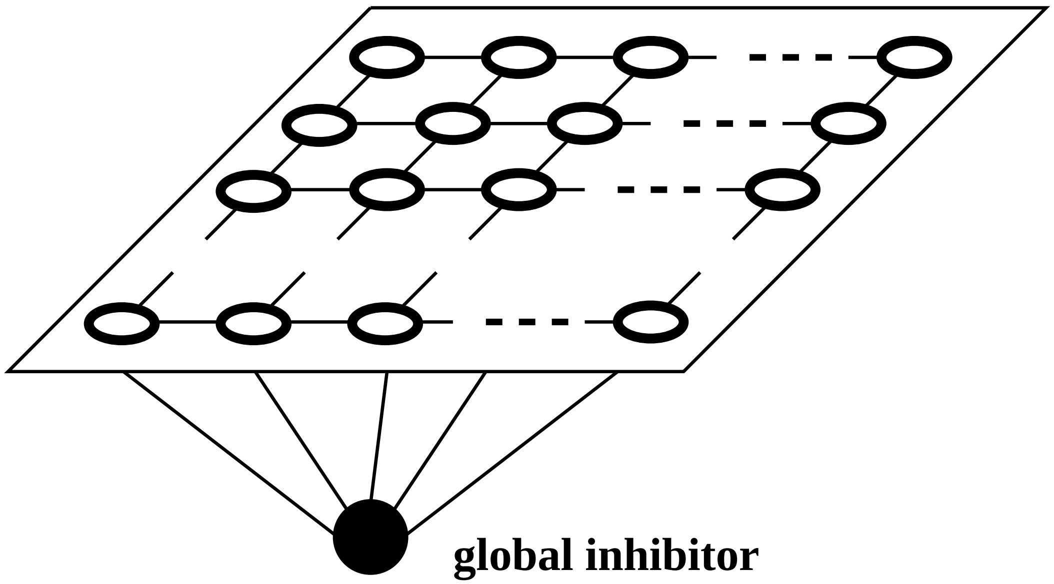
LEGION Model

- Oscillatory Correlation
  - Temporal correlation theory (Milner, 1974; vor den Malsburg, 1981): an object is represented by the temporal correlation of the firing activities of the distributed cells that detect different features of the object.
  - Oscillatory correlation (Wang & Terman, 1995) provides a special form of temporal correlation; where each object is represented by a group of synchronized oscillators and different objects are represented by different groups whose oscillations are desynchronized each other.

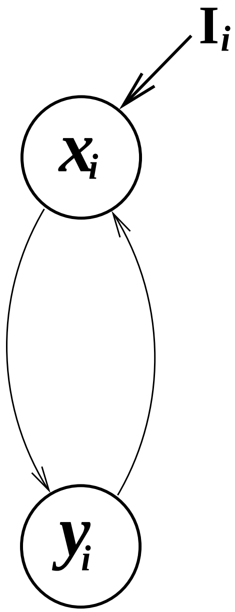
LEGION Model

- LEGION: Locally Excitatory Globally Inhibitory Oscillator Networks (Terman & Wang, 1995; Wang & Terman, 1995)

Architecture



Single Oscillator



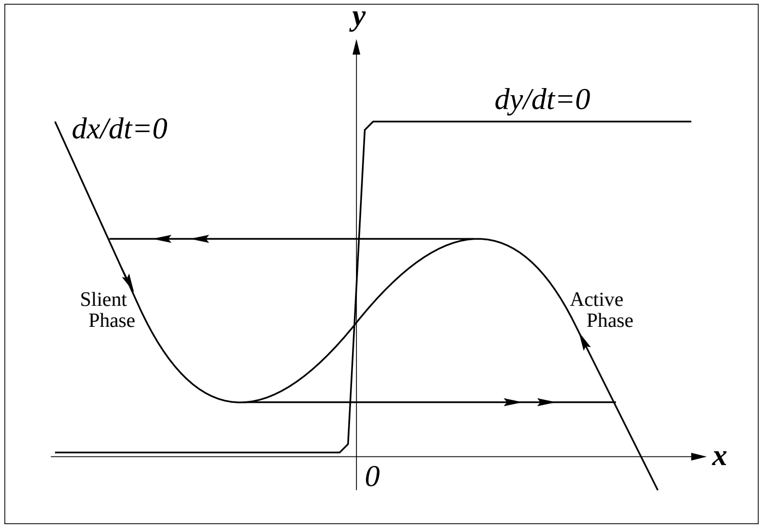
LEGION Model

- Dynamics: Single Oscillator

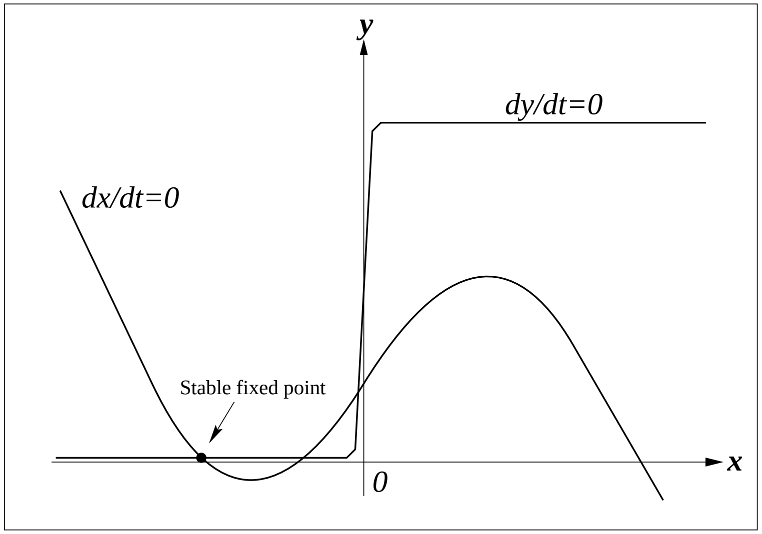
$$\frac{dx_i}{dt} = 3x_i - x_i^3 - y_i + I_i + S_i + \rho \qquad \text{(1a)}$$

$$\frac{dy_i}{dt} = \epsilon\Big(\lambda + \gamma \tanh(\beta x_i) - y_i\Big). \qquad \text{(1b)}$$

$I_i > \lambda - \gamma + 2$



$I_i < \lambda - \gamma + 2$



LEGION Model

- Coupling Term (Campbell & Wang, 1998)

$$S_i = \sum_{k \in N(i)} W_{ik} S_\infty(x_k(t-\tau), \theta_x) - W_z S_\infty(z, \theta_z), \tag{2}$$

where $S_\infty(x, \theta) = 1/\big(1 + \exp[-\kappa(x-\theta)]\big)$ and $\tau \geq 0$.

- Global Inhibitor

$$\frac{dz}{dt} = \phi(\sigma_\infty - z). \tag{3}$$

where $\sigma_\infty = 0$ if $x_i < \theta_z$ for every oscillator i, and $\sigma_\infty = 1$ if $x_i(t) \geq \theta_z$ for at least one oscillator i.

- Dynamics of LEGION: A process of both synchronization by local cooperation through excitatory coupling among neighboring oscillators, and desynchronization by global competition via the global inhibitor.

Methodology

- 2-D LEGION Network: each oscillator corresponds to one pixel
- Pattern Formation: min-max difference measure

$$|t^i - t^j| < \tau_{RB} \text{ and } |t^i - t^k| \geq \tau_{RB}$$

  where τ_{RB} is the time period of an active phase.

- Intuitively, pattern formation is achieved when all the oscillators corresponding to the same pattern are simultaneously active during a time period, and oscillators belonging to different patterns are never active simultaneously; otherwise pattern formation is not achieved.
- Time delay is inevitable in information transmission of a biological system.

Simulations

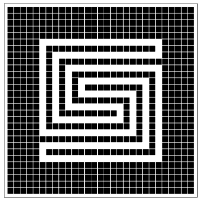
- LEGION is applied to The Spiral Problem (Minsky and Papert, 1969), Two-Spiral Problem (Benchmark; Fahlman, 1993), and Inside/Outside Relations (Ullman, 1984).

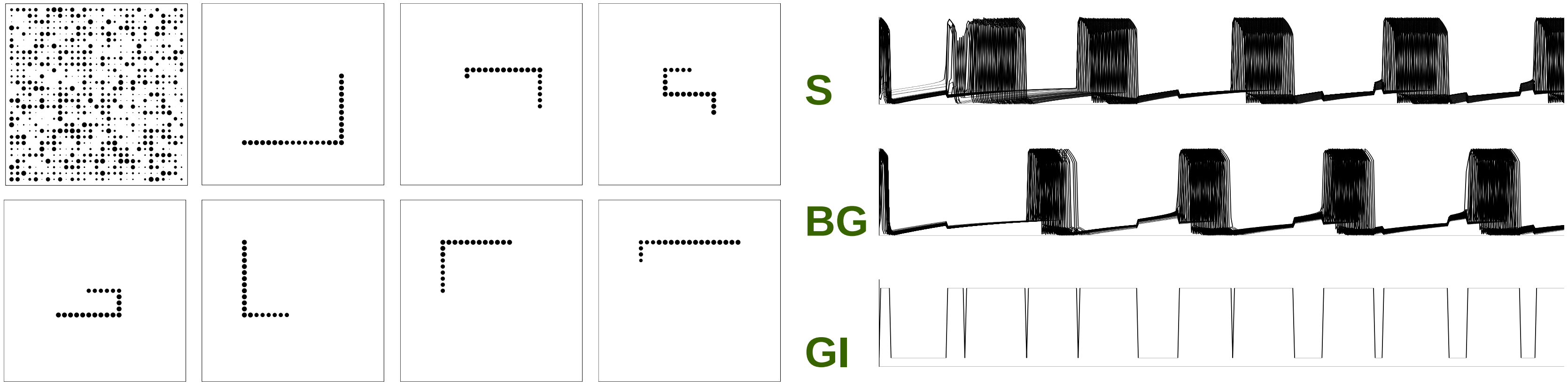
- Stimuli: Binary images sampled from the original figures

- Representation of Results: Snapshots showing temporal evolution and combined x activities of the oscillators representing the same object and the global inhibitor over time.

Simulations

Results of The Spiral Problem (I): Time Delay

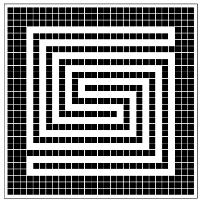


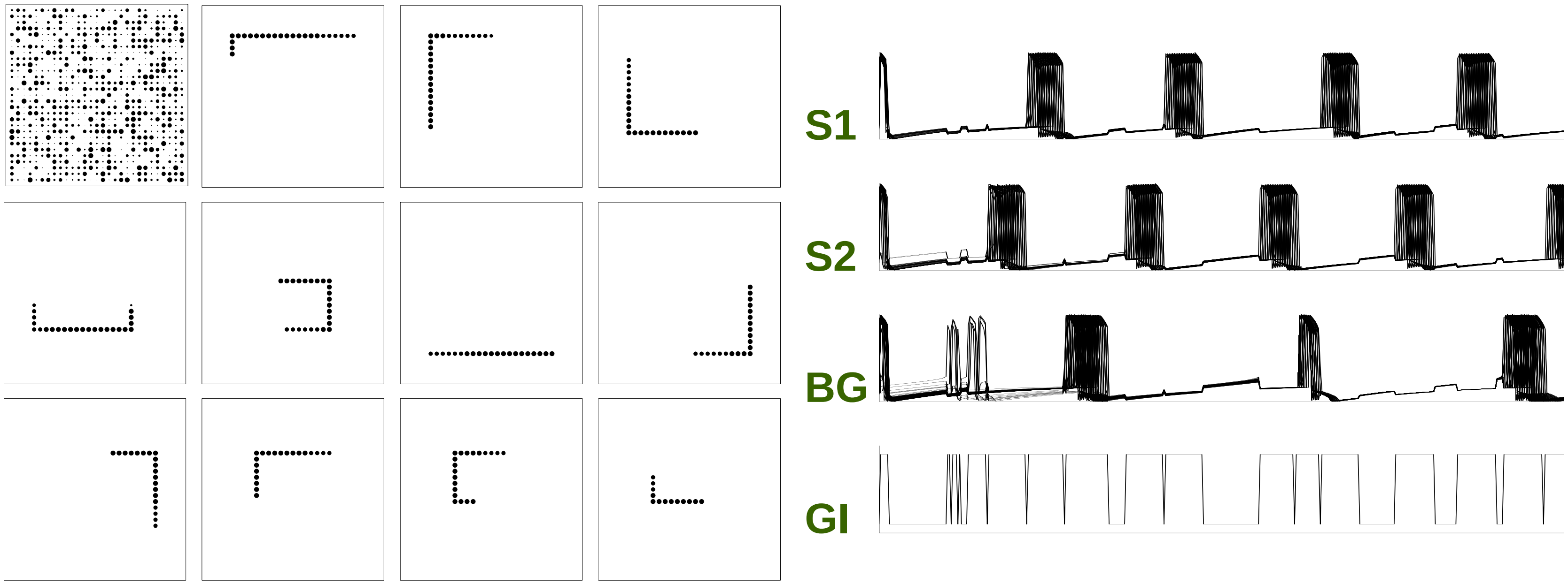


Pattern formation is not exhibited.

Simulations

Results of The Spiral Problem (II): Time Delay

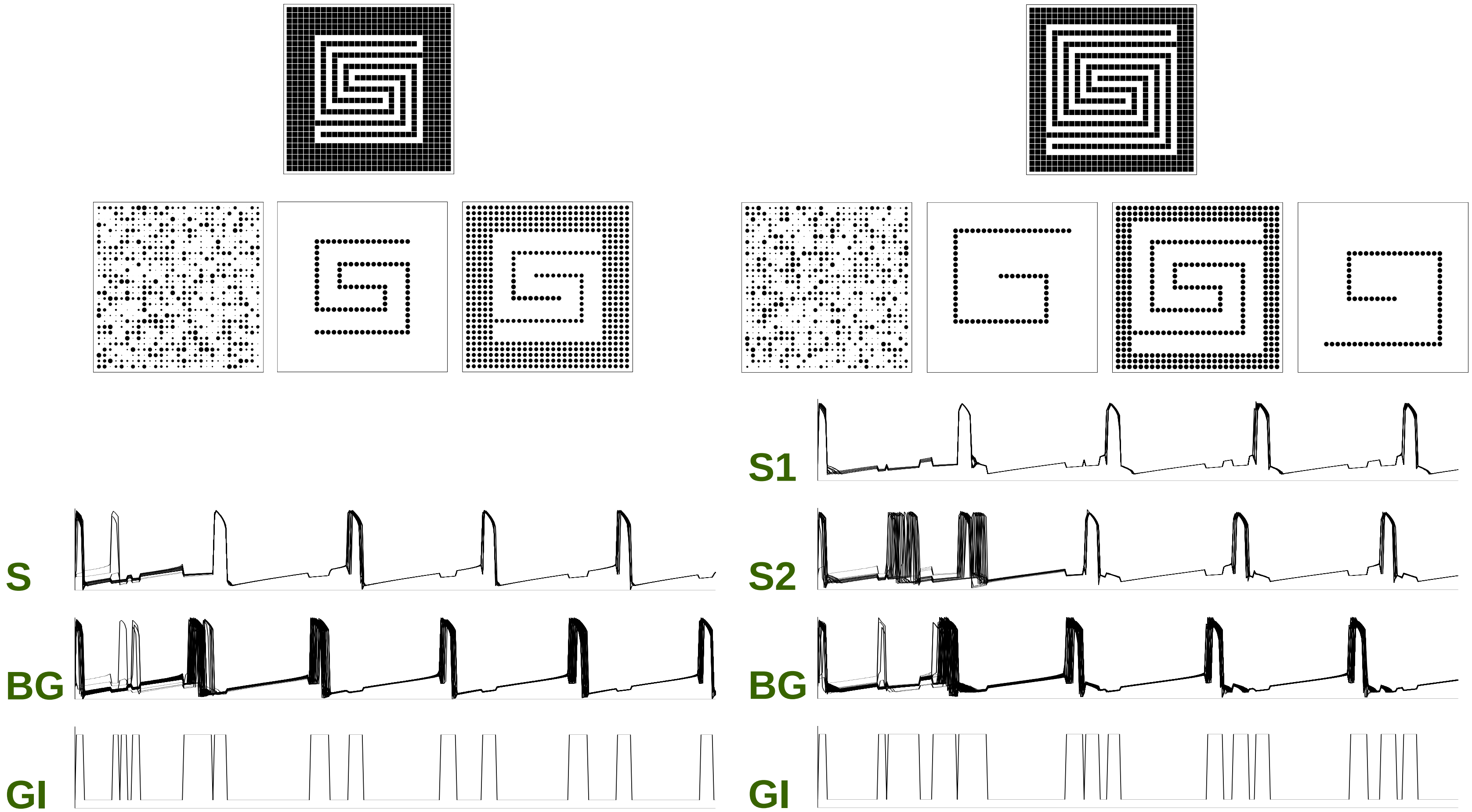




Pattern formation is not exhibited.

Simulations

Results of The Spiral Problem (III): No Time Delay

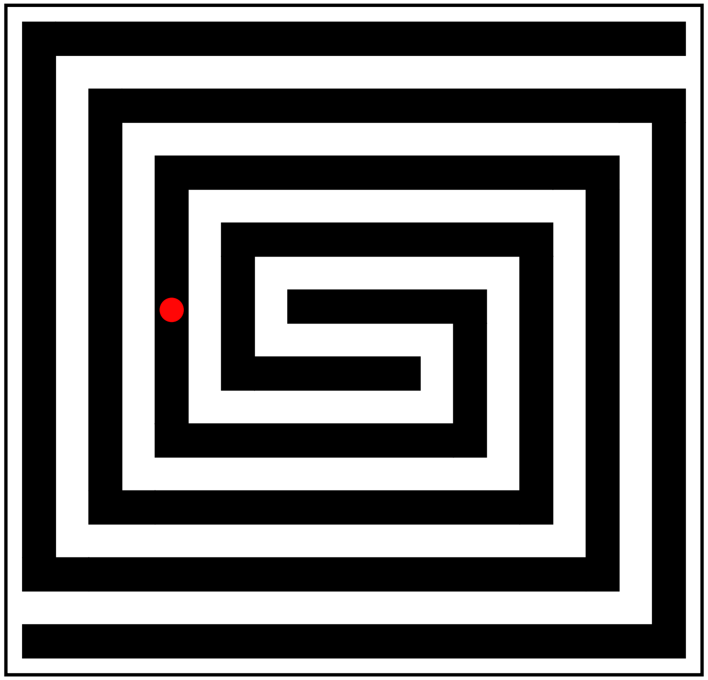


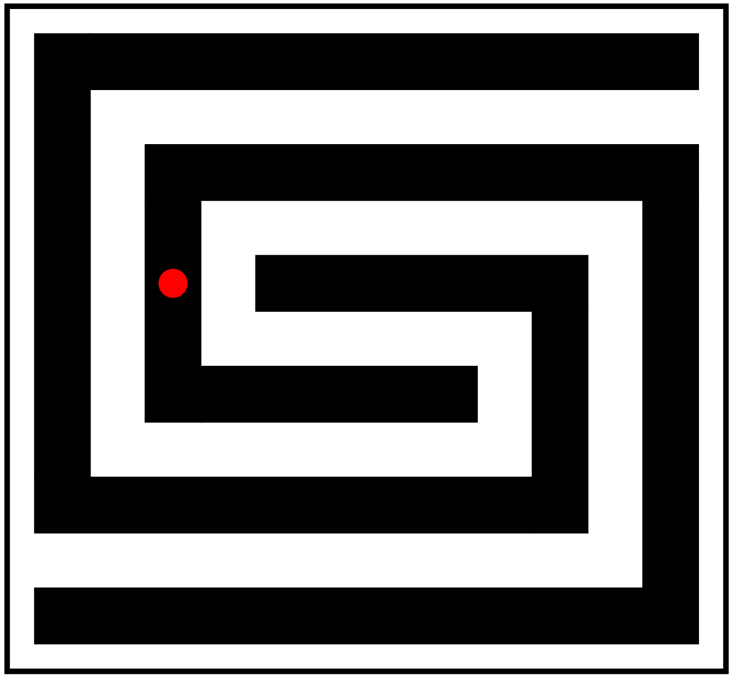
Pattern formation is exhibited.

Simulations

Two-Spiral Problem

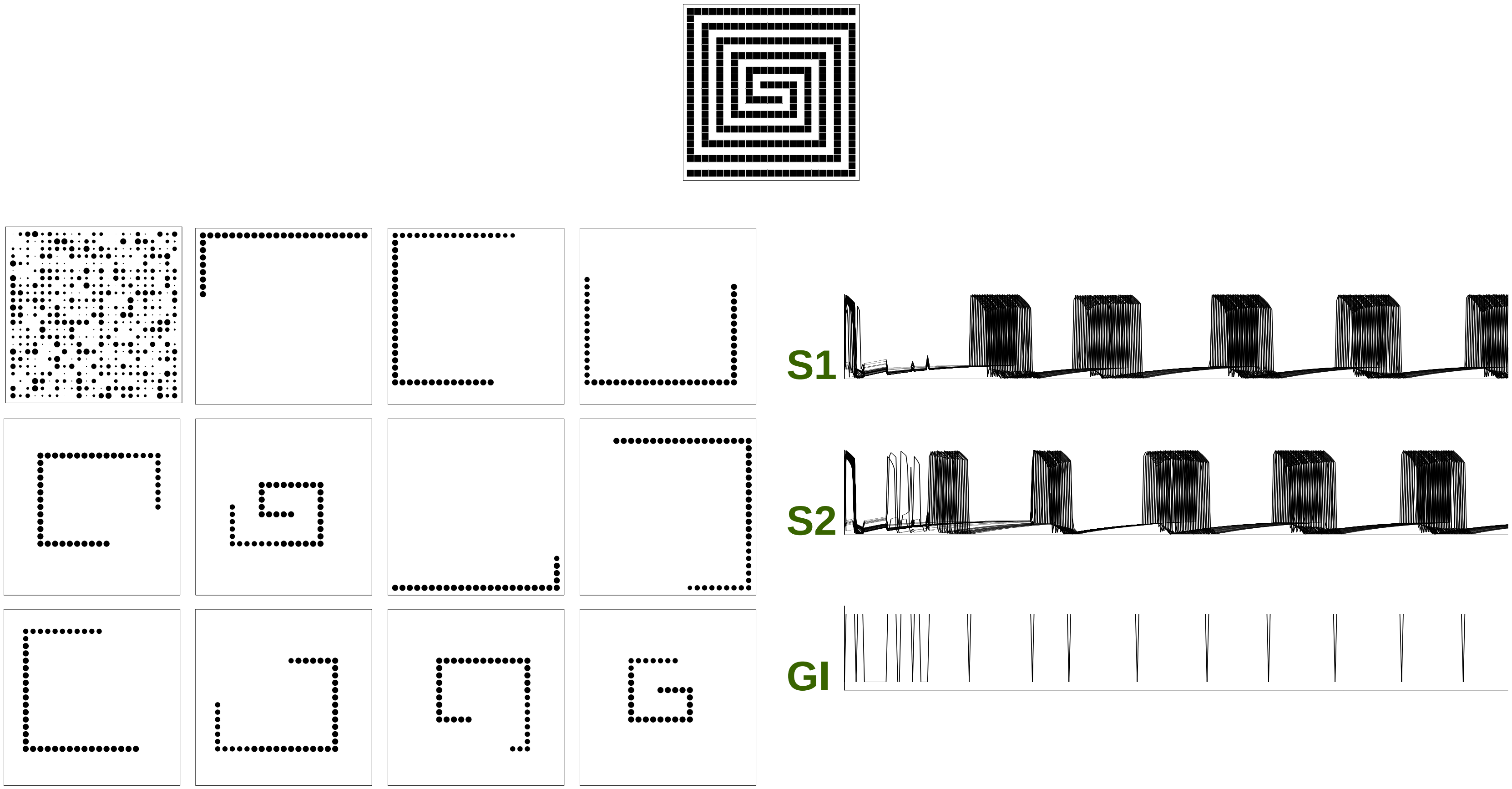
Given a point on one of the two spirals, determine which spiral does the point lie on?





Simulations

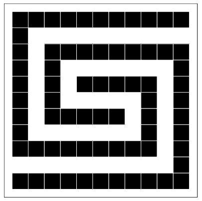
Results of Two-Spiral Problem (I): Time Delay

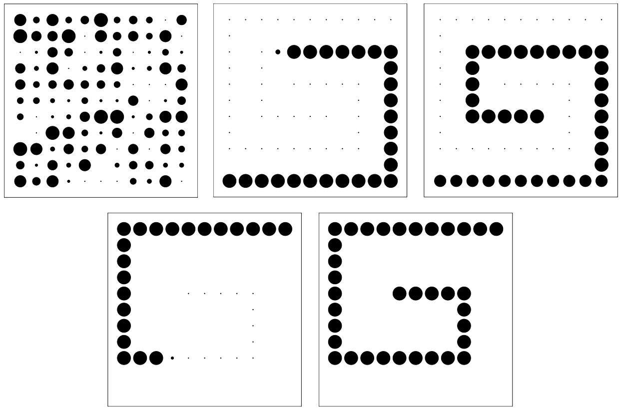


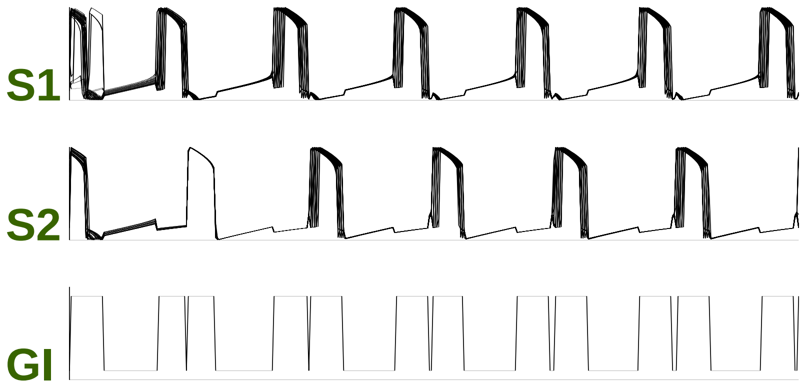
Pattern formation is not exhibited.

Simulations

Results of Two-Spiral Problem (II): Time Delay



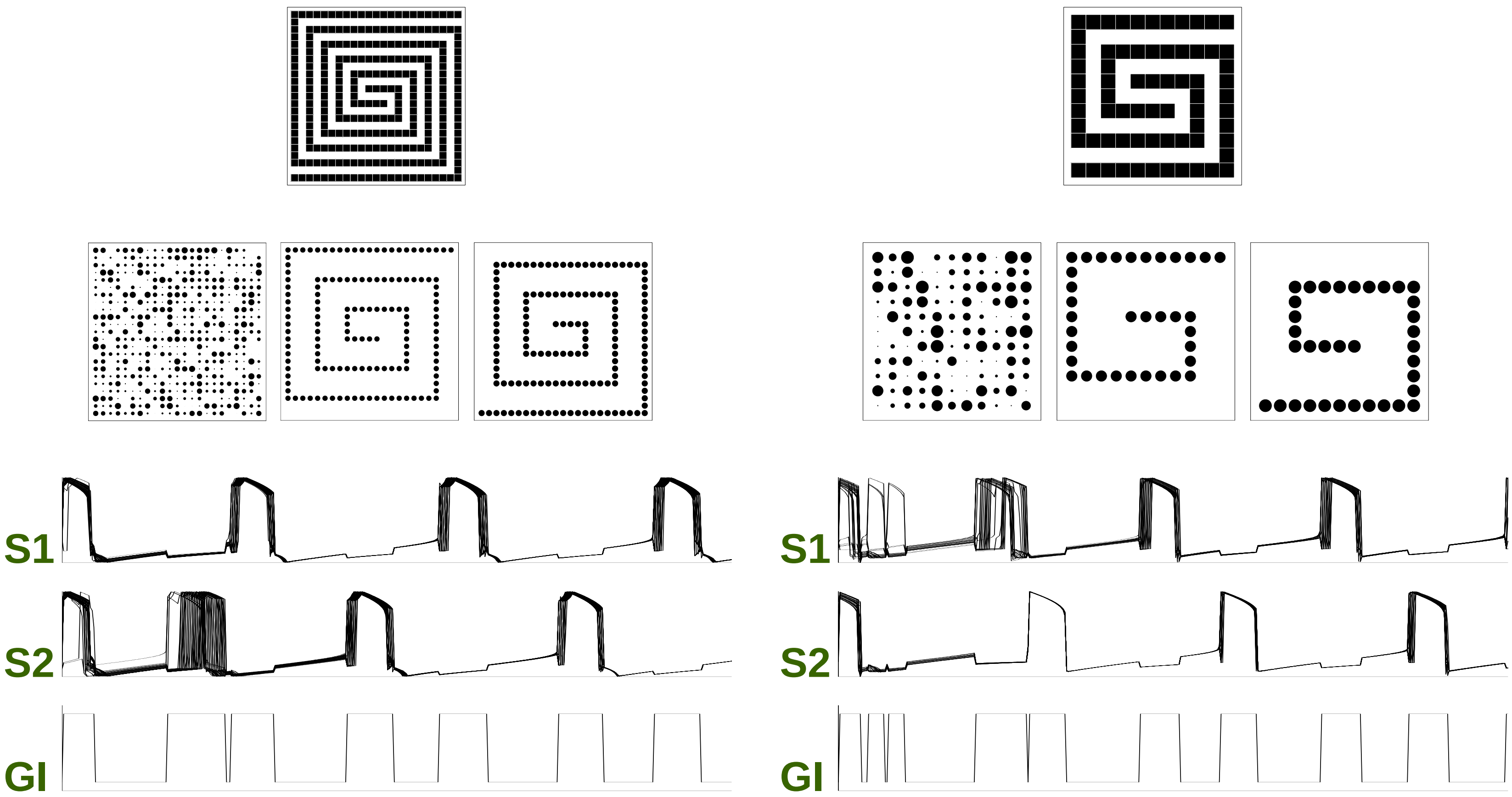




Pattern formation is exhibited.

Simulations

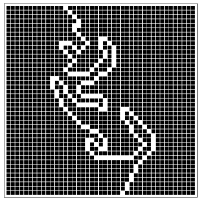
Results of Two-Spiral Problem (III): No Time Delays

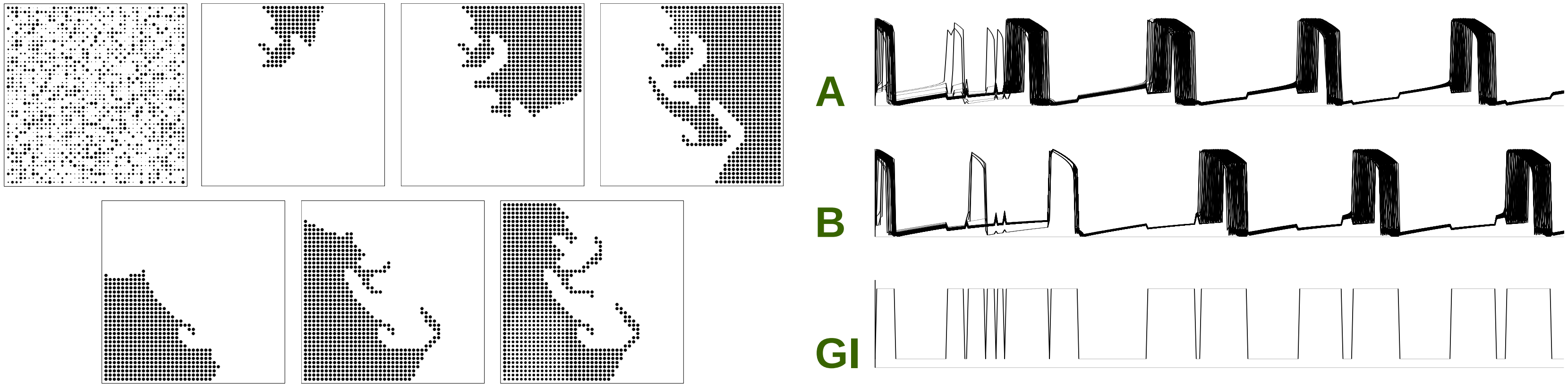


Pattern formation is exhibited.

Simulations

Results of Inside/Outside Relations (I): Time Delay

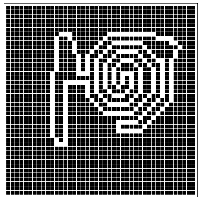


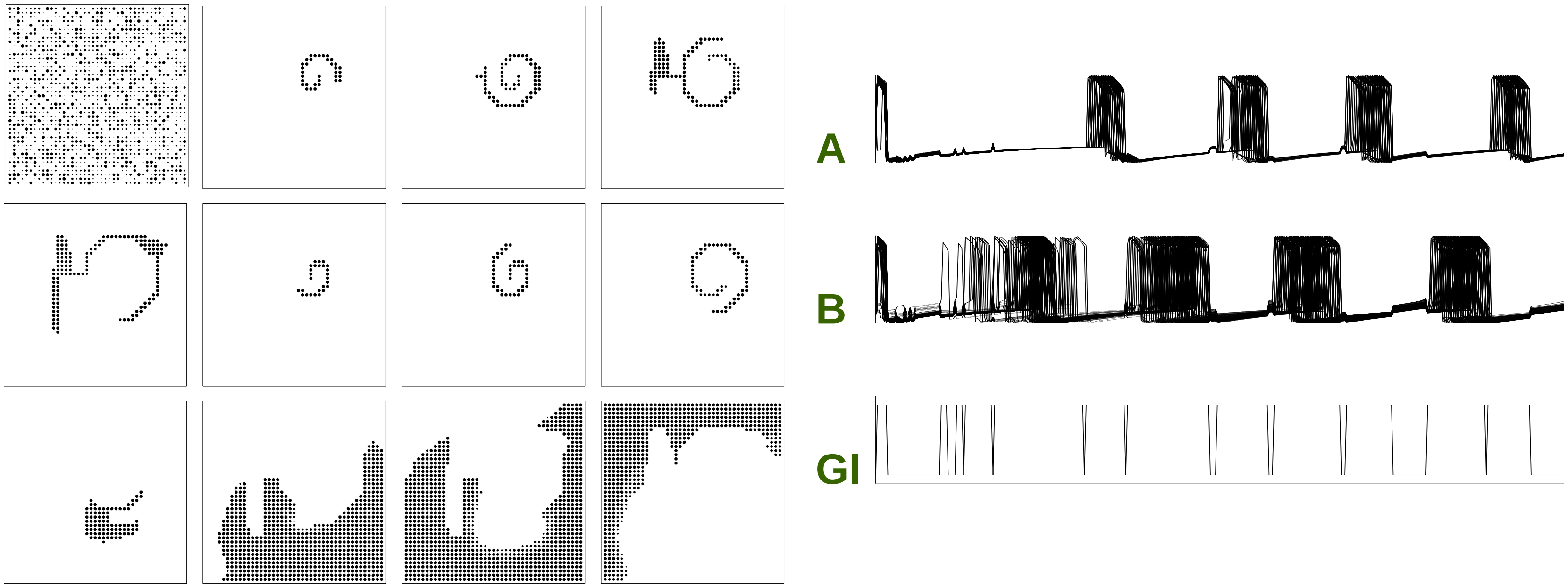


Pattern formation is exhibited.

Simulations

Results of Inside/Outside Relations (II): Time Delay

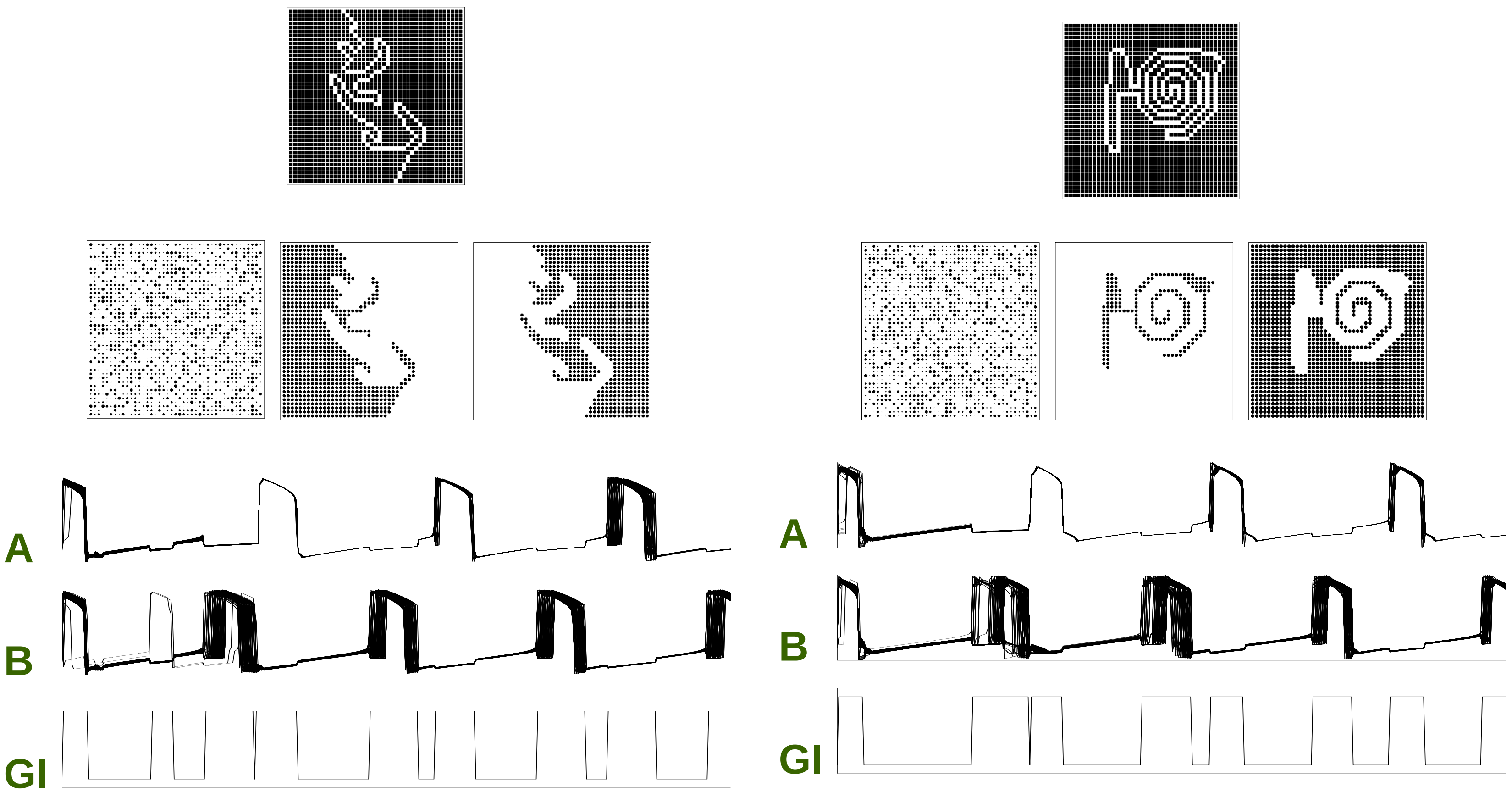




Pattern formation is not exhibited.

Simulations

Results of Inside/Outside Relations (III): No Time Delay



Pattern formation is exhibited.

Discussion

- On Learning for The Spiral Problem
  - Although many neural network models can solve the problem via learning, their solutions are limited to a given training set.
  - Solving the spiral problem is equivalent to detecting connectedness which cannot be computed by order-limited perceptrons (Minsky & Papert, 1969).
  - The limitation holds for multi-layered perceptions regardless of learning scheme (Minsky & Papert, 1988, p.252).
  - In contrast, LEGION without time delays can always distinguish these figures regardless of shape, position, size, and orientation.

Discussion

- Biological Plausibility
  - Both neural oscillations and time delays are biologically plausible mechanisms.
- Interpretation of Our Results
  - An active oscillator in a locally coupled neural network can only propagate its activation to its neighbors. Thus, spiral-like regions constrain propagation so that activation slowly spreads along the spiral structure.
  - For detecting connectedness, global information is necessary. However, global information is not available until pattern formation is achieved in the framework of oscillatory correlation.
  - The dilemma might be responsible for human limitations in perceiving this kind of visual stimuli.

Discussion

- On Inside/Outside Relations
  - Based on oscillatory correlation, LEGION provides a way to model the perception of inside/outside relations.
  - Our method is quite different from visual routines (Ullman, 1984; 1996):
    - The visual routines approach is described as serial algorithms, whereas ours is inherently parallel and distributed. Our results demonstrate that such visual functions may be achieved with a mechanism as primitive (early) as that for image segmentation.
    - Visual routines do not make a qualitative distinction between rapid (effortless) perception and slow (effortful) perception. In contrast, ours does.

Conclusion

- Using oscillatory correlation, we have given a generic solution to the spiral and inside/outside problems without learning.
- We find that the spiral and inside/outside problems share an intrinsic property: rapid perception is limited if local activation cannot rapidly spread, as synchrony would not be established in the presence of time delays.
- Our simulation results of LEGION with time delays qualitatively resemble human performance, while LEGION without time delays always solves these problems.
- We suggest that this kind of topological/geometrical problems may be better addressed by proper network architectures rather than sophisticated learning schemes.