Learning C. elegans locomotion and foraging with a hierarchical space-time cellular automaton

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Abstract

For decades, the tiny nematode worm C. elegans has been and continues to be a fount of biological information. Like all living things, this relatively simple creature survives and propagates in an environment that is fundamentally structured in space and time. The environment generates sequences of stimuli that produce sensory events within an organism and the organism responds to spatially navigate and manipulate the environment. Thus space and time are universalities that all living things must in some way reflect and represent. In biological research, the general aim is to discover how a species functions in some way. For this project, however, the behavior of C. elegans is analyzed with the aim of testing the applicability of an underlying common informational mechanism that models aspects of animal behaviors in general. The model is called *morphognosis* (*morpho* = shape and *gnosis* = knowledge). Its basic structure is a pyramid of event recordings. At the apex of the pyramid are the most recent and nearby events. Receding from the apex are less recent and possibly more distant aggregated events. In this project, the locomotion and foraging behaviors of C. elegans are learned and reproduced by morphognosis. A cellular automaton implements morphognosis, meaning that the locomotion and foraging behaviors are decomposed into cellular automaton rules which are then learned by an artificial neural network that is capable of generalizing to handle novel environmental stimuli.

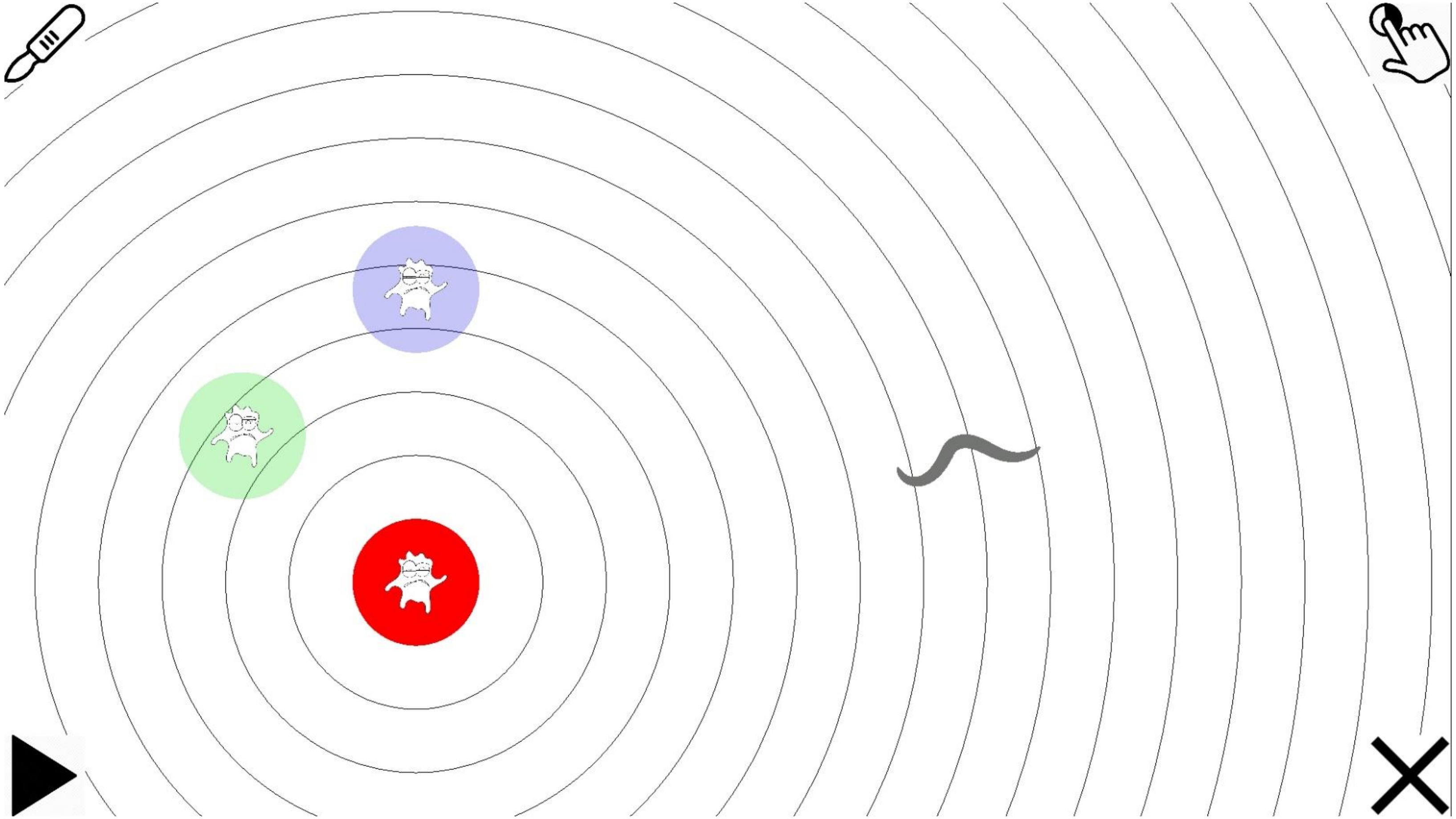
Overview

- Animal behavior operates in space and time.
  - For example, in mammals specific brain structures are involved: “The hippocampus is this grand organizer of memories in space and time. It provides a spatiotemporal framework onto which other events are applied.” – H. Eichenbaum
- Can a model that incorporates space and time capture a wide variety of behaviors?
- The proposed model learns by decomposing behavior into hierarchical/contextual space-time rules.
- In this project, the foraging and locomotion behavior of C. elegans is decomposed.

C. elegans locomotion and food foraging

- C. elegans is a 1mm nematode worm comprised of 1000 cells and found in temperate soils.
- Locomotion is sinusoidal, both crawling and swimming.
- One of the worm’s food sources is bacteria which produce salt that diffuses into the environment.
- The worm follows salt gradients to find food (klinotaxsis) using a pair of sensory neurons in the head (ASL and ASR).
- A neuromuscular simulation provided by Boyle, Berri and Cohen (2012) was used to supply the locomotion data.
- A study by Izquierdo and Beer (2015) provided the foraging behavior.

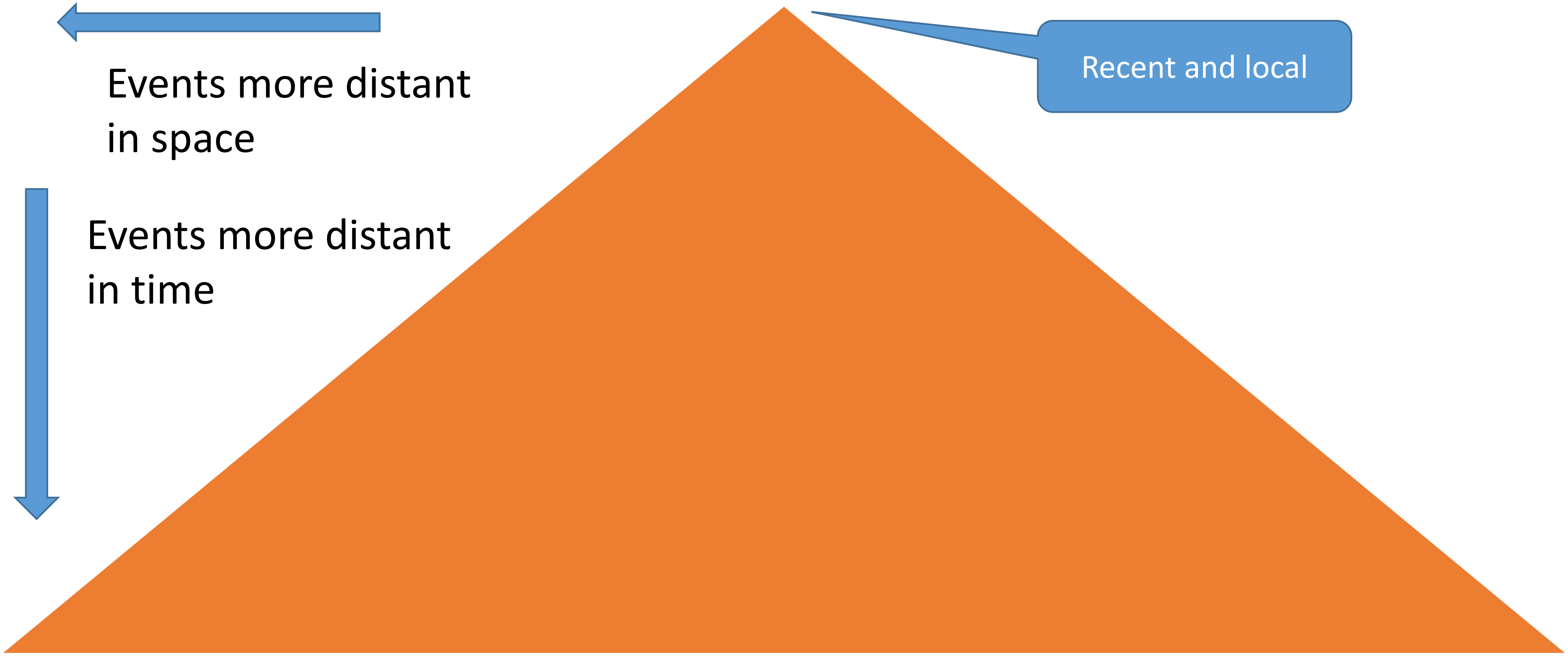
Foraging along salt gradients



The *Morphognosis* model

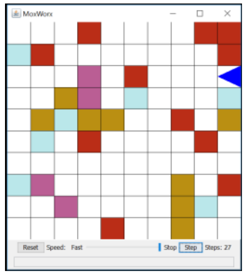
- Definition: *morpho* = shape and *gnosis* = knowledge.
- Implemented as a cellular automaton but can be extended to other computing schemes.
- Learns how an organism behaves in its environment.
- A basic structure is a pyramidal hierarchy of event recordings called a *morphognostic*.
  - At the apex of the pyramid are the most recent and nearby events. Receding from the apex are less recent and possibly more distant events.
  - More recent and less distant events are encoded with greater precision that older and more distant events for linear complexity growth.

Morphognostic pyramid

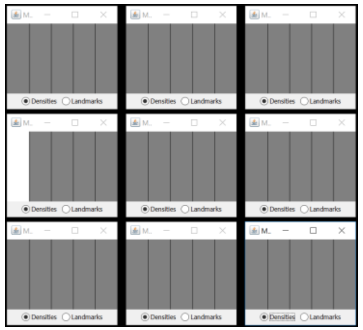


Pyramid of cell type densities arranged as hierarchy of 3x3 cell neighborhoods

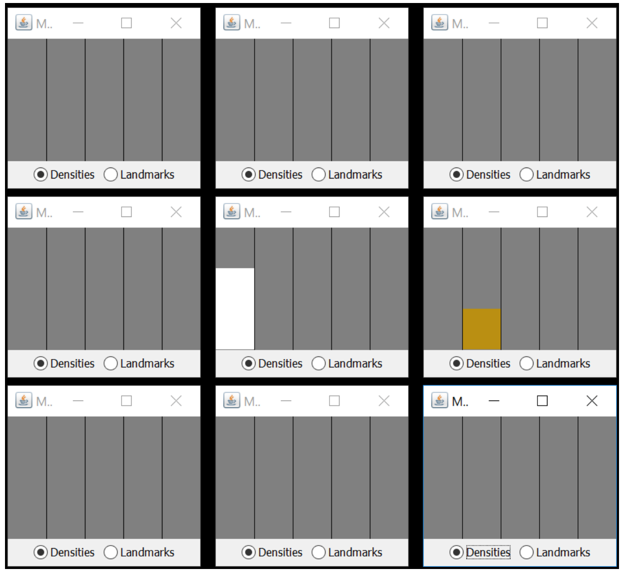
Less recent and more distant



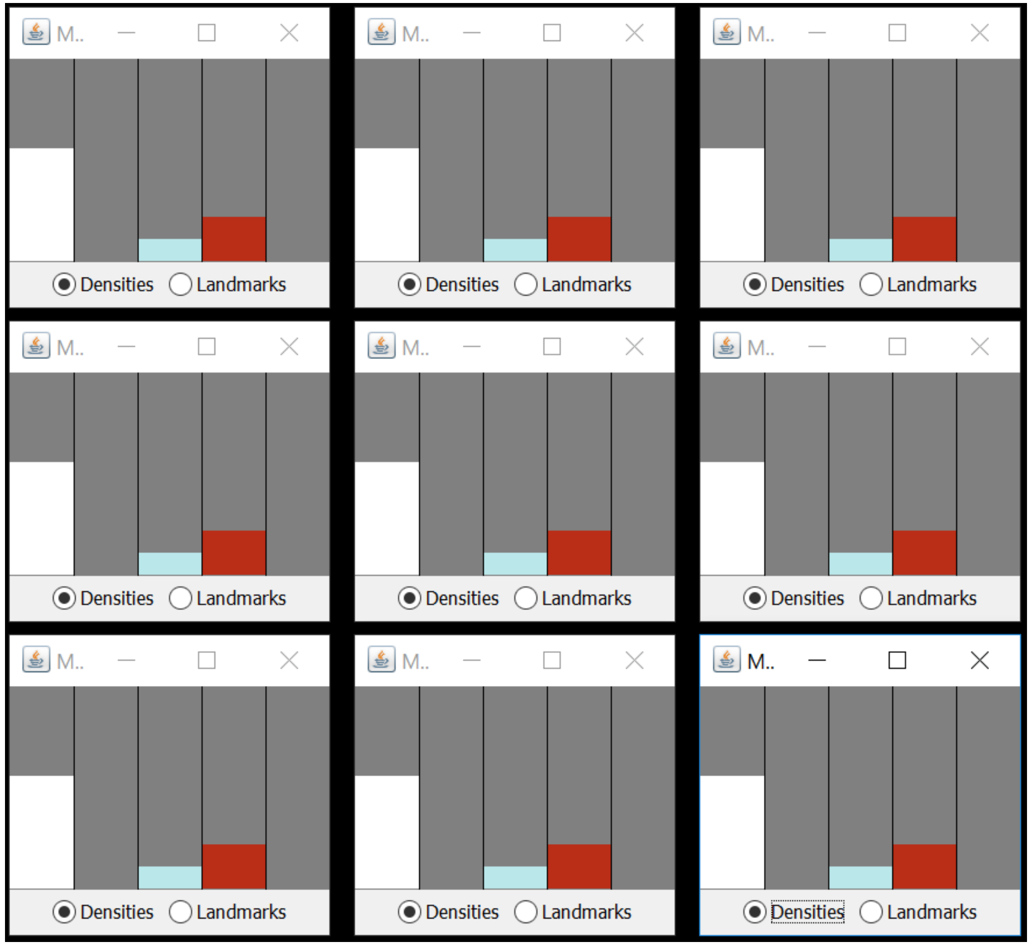
3x3



(3x3)x(3x3)=9x9



(9x9)x(9x9)=27x27



Morphognostic spatial neighborhoods

A cell defines an elementary neighborhood:

$neighborhood_0 = cell$

A non-elementary neighborhood consists of an *NxN* set of *sectors* surrounding a lower level neighborhood:

$neighborhood_i = NxN(neighborhood_{i-1})$

where N is an odd positive number.

Morphognostic (cont.)

The value of a sector is a vector representing a histogram of the cell type densities contained within it:

value(sector) = (density(cell-type$_0$), density(cell-type$_1$), … density(cell-type$_n$))

The number of cells contributing to the density histogram of a sector of *neighborhood$_i$* = $N^{i-1} x N^{i-1}$

Morphognostic temporal neighborhoods

A neighborhood contains events that occur between time *epoch* and *epoch* + *duration*:

$$t1_0 = 0$$

$$t2_0 = 1$$

$$t1_i = t2_{i-1}$$

$$t2_i = (t2_{i-1} * 3) + 1$$

$$epoch_i = t1_i$$

$$duration_i = t2_i - t1_i$$

Metamorphs

A *metamorph* embodies a cellular automaton rule: morphognostic→response.

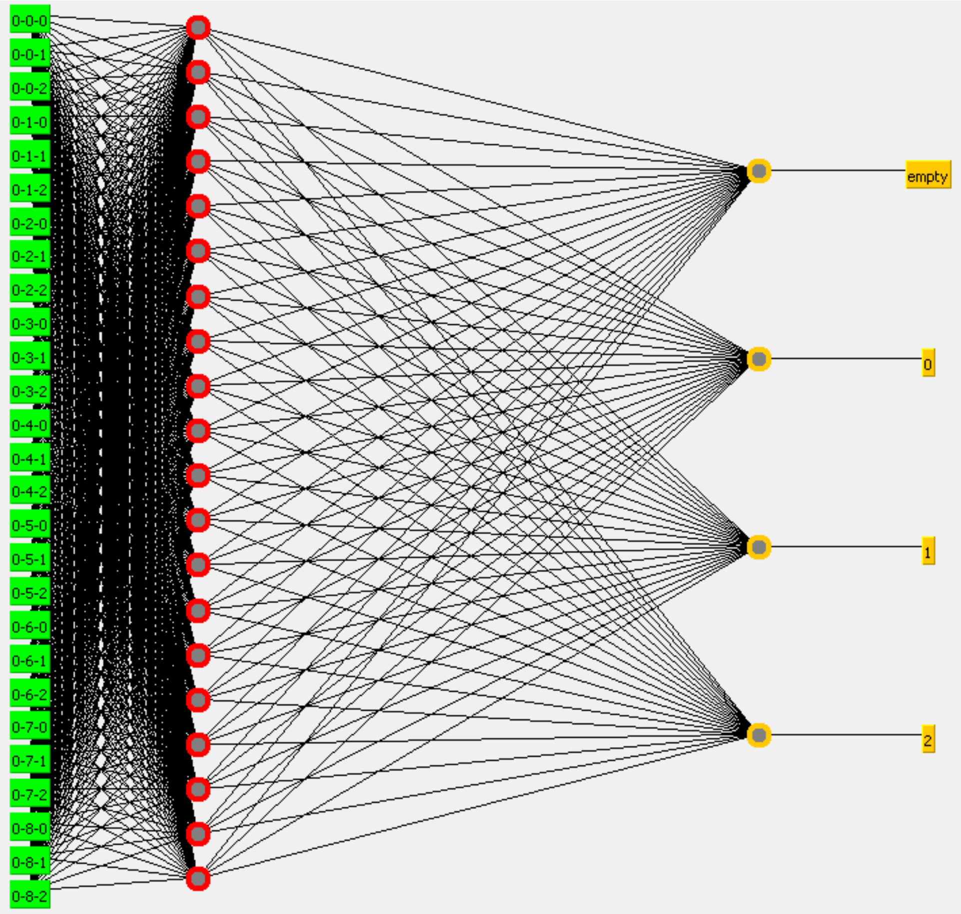
Metamorph “execution” consists generating a morphognostic for the current environmental state and then finding the least distant morphognostic contained in the learned set, where:

$$distance(metamorph_i, metamorph_j) = \sum_{x}^{neighborhoods} \sum_{y}^{sectors} \sum_{z}^{cell\ types} abs(cell\ type\ density_{i,x,y,z} - cell\ type\ density_{j,x,y,z})$$

Metamorph artificial neural network implementation (more compact, faster)

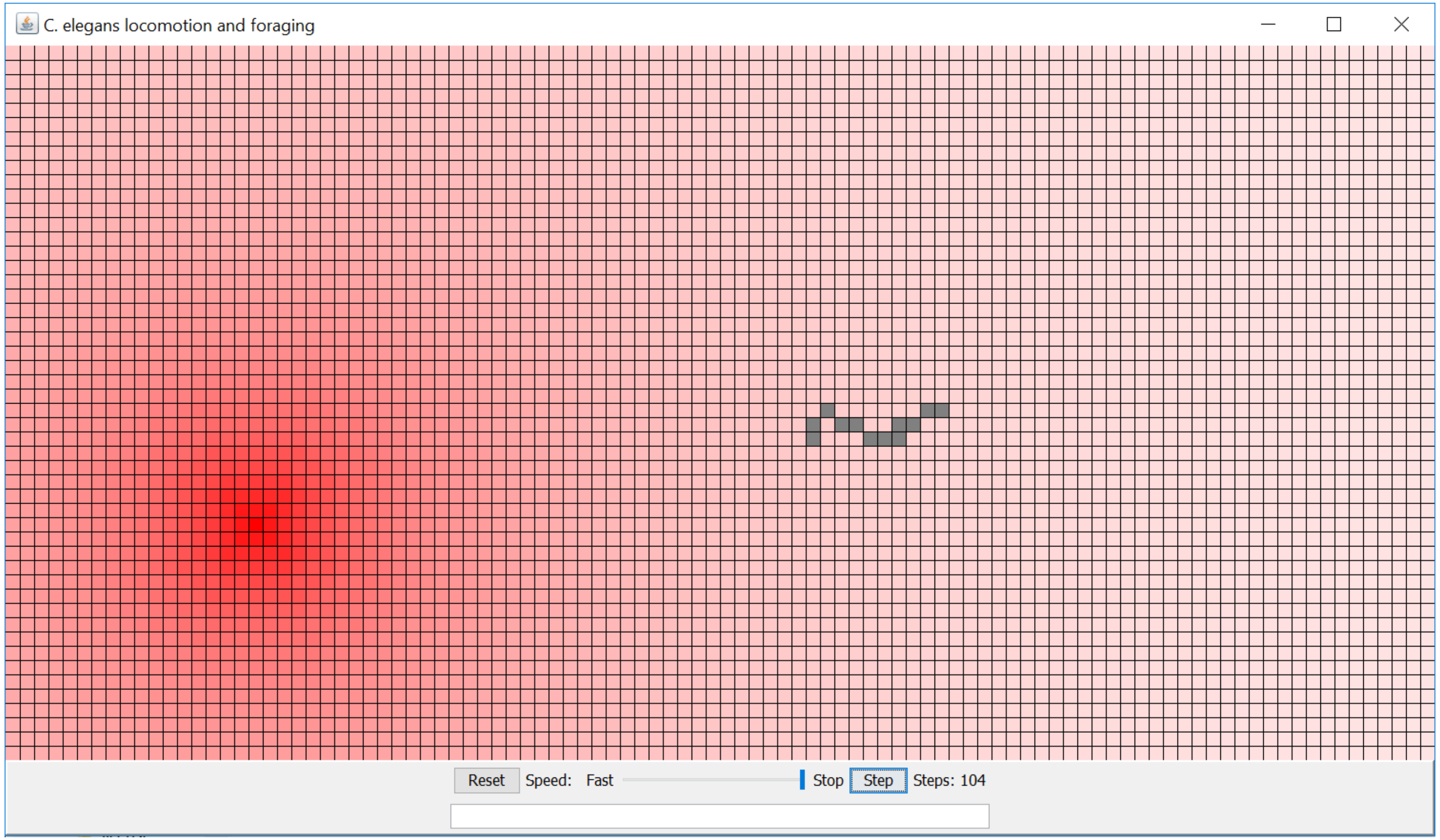
Input: morphognostic neighborhood cell type densities

Key: neighborhood-sector-cell type



Output: response

C. elegans food foraging in cellular automaton



Procedure

- Worm is “digitized” into grid of cells.
- Two sets of rules:
  - Worm head senses and responds to salt gradient.
  - Body cells simulate locomotion.
- Simulation initially runs during which rules are learned.
- Worm runs from rules.

Results

- Three “colors” of food (red, blue, green) presented sequentially at different locations.
- Worm is capable of learning to reach all colors.
- Worm is capable of changing course when food is moved mid-route.
- Head rule set: 728 rules.
- Body rule set: 3359 rules.

What’s next?

Pufferfish nest building.

Male pufferfish creates complex structures on sea bed to attract mate:

More to explore

Thomas Portegys, "Morphognosis: the shape of knowledge in space and time", The 28th Modern Artificial Intelligence and Cognitive Science Conference (MAICS), 2017.

Boyle, Berri and Cohen, “Gait modulation in C. elegans: an integrated neuromechanical model”, Front. Comput. Neurosci., 2012.

Eduardo J. Izquierdo and Randall D. Beer, "An Integrated Neuromechanical Model of Steering in C. elegans", ECAL15

“Who Let The Dogs Out? Modeling Dog Behavior From Visual Data”, Kiana Ehsani, Hessam Bagherinezhad, Joseph Redmon, Roozbeh Mottaghi, Ali Farhadi, https://arxiv.org/abs/1803.10827

Modeling hydra behavior by metrics: http://neurosciencenews.com/ai-animals-8919/

Code: https://github.com/morphognosis/WormWorx

WormWorx Android app: http://wormworx.portegys.com/