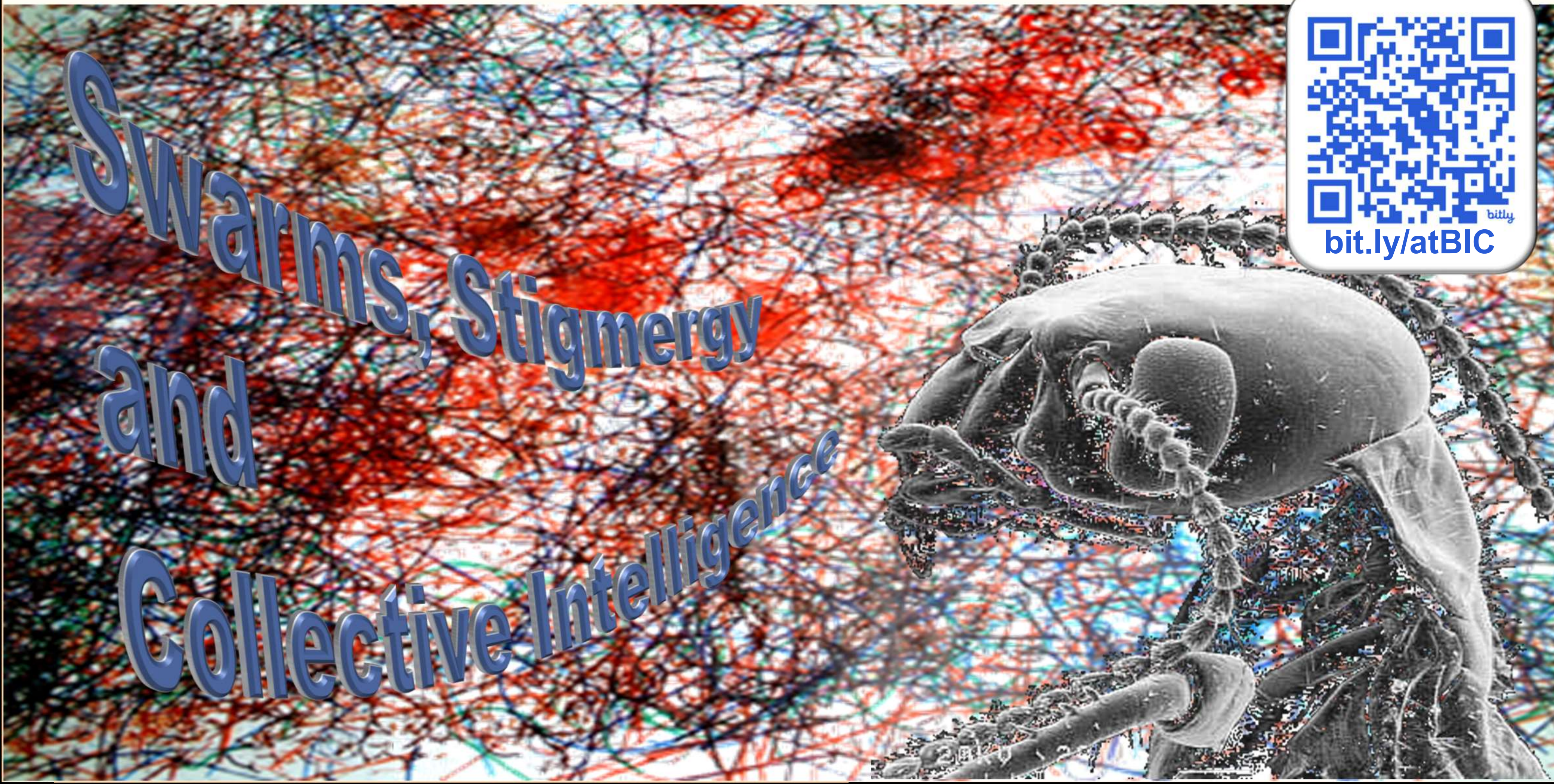
lecture 14

Swarms, Stigmergy and Collective Intelligence



bit.ly/atBIC

key events coming up

- Labs: 35% (ISE-483)
  - Complete 5 (best 4 graded) assignments based on algorithms presented in class
    - Lab 4 : April 22nd (Tuesday after Easter break)????
      - Evolutionary Algorithms, (Assignment 4)
        - Delivered by Kristen Beideman
        - Due **April 29th**
    - Lab 5: April 28th
      - Ant Clustering Algorithm, (Assignment 5)
        - Delivered by Emad Abed and Kiet Ngo Tuan
        - Due May 5th
- SSIE – 583 -Presentation and Discussion: 25%
  - Present and lead the discussion of an article related to the class materials
    - Enginet students post/send video or join by Zoom

bit.ly/atBIC

BINGHAMTON UNIVERSITY STATE UNIVERSITY OF NEW YORK
rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

- Projects
  - **Due by May 7th** in Brightspace, “Final Project 483/583” assignment
    - ALIFE 2025
      - Not necessarily to submit to actual conference due date
        - May 4 full paper, July 4, abstract
      - https://2025.alife.org/
      - Max 8 pages, author guidelines:
      - https://2025.alife.org/calls#paper-call
      - MS Word, PDF, and Latex/Overleaf templates.
  - Individual or group
    - With very definite tasks assigned per member of group

ALIFE 2025

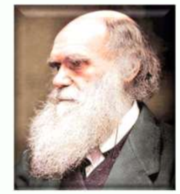
Tackle a real problem using bio-inspired algorithms, such as those used in the labs.

bit.ly/atBIC

Reusing and expanding labs is highly encouraged.

until now

- Class Book
  - Floreano, D. and C. Mattiussi [2008]. *Bio-Inspired Artificial Intelligence: Theories, Methods, and Technologies*. MIT Press.
    - Chapters 1, 2, 4, **and 7**
- Lecture notes
  - Chapter 1: What is Life?
  - Chapter 2: The logical Mechanisms of Life
  - Chapter 3: Formalizing and Modeling the World
  - Chapter 4: Self-Organization and Emergent Complex Behavior
  - Chapter 5: Reality is Stranger than Fiction
  - Chapter 6: Von Neumann and Natural Selection
  - Chapter 7: Modeling Evolutionary Systems
    - posted online @ http://informatics.indiana.edu/rocha/i-bic
- Papers and other materials
  - Optional
    - Nunes de Castro, Leandro [2006]. *Fundamentals of Natural Computing: Basic Concepts, Algorithms, and Applications*. Chapman & Hall.
      - Chapter 2, 7, 8
      - **Chapter 3, sections 3.1 to 3.5**



BINGHAMTON UNIVERSITY STATE UNIVERSITY OF NEW YORK
rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

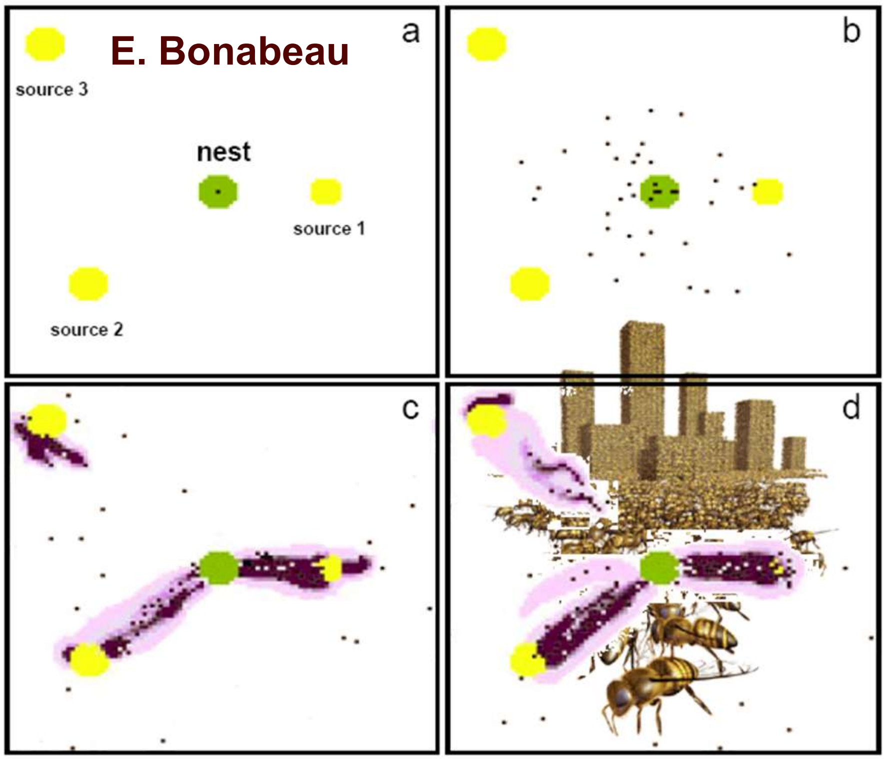
differences and explanations

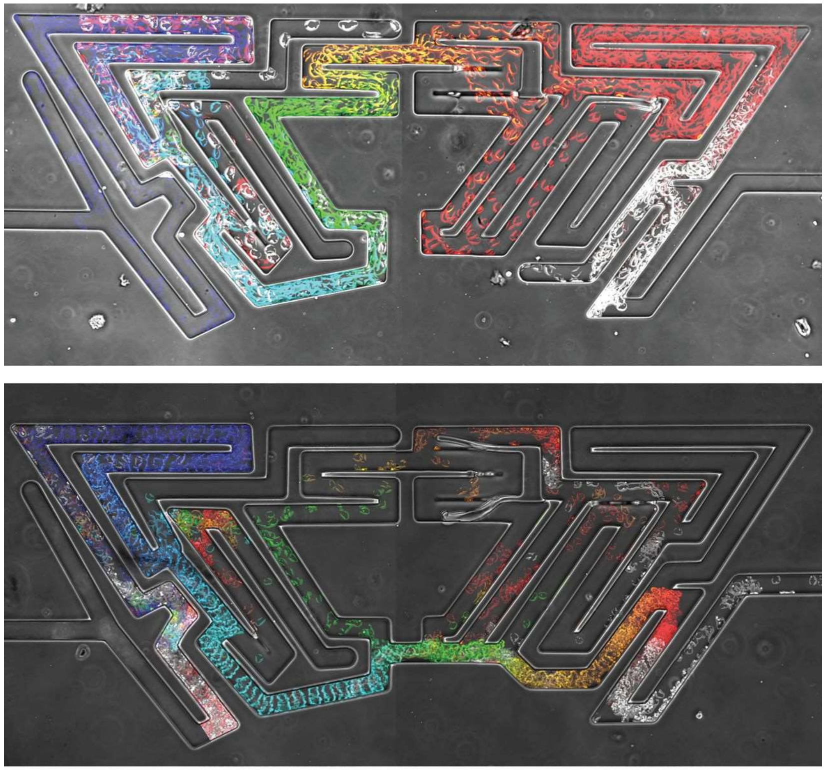
- Emergent behavior
  - Intricate structures and behavior from the interaction of many simple agents or rules
- Examples
  - Cellular Automata, Ant colonies, development, morphogenesis, brains, immune systems, economic markets
- Mechanism
  - Parallelism, multiplicity, stigmergy, multi-solutions, redundancy
- Design causes
  - Natural selection, self-organization, epigenetics, language, culture

Collective Behavior

rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

pheromone evaporation and self-generated chemoattractants

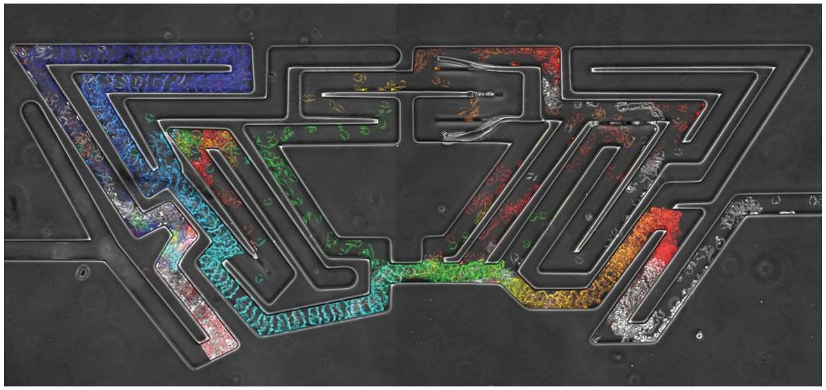




Tweedy, et al [2020]. "Seeing around Corners: Cells Solve Mazes and Respond at a Distance Using Attractant Breakdown." *Science* **369** (6507): eaay9792.

rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

pheromone evaporation and self-generated chemoattractants

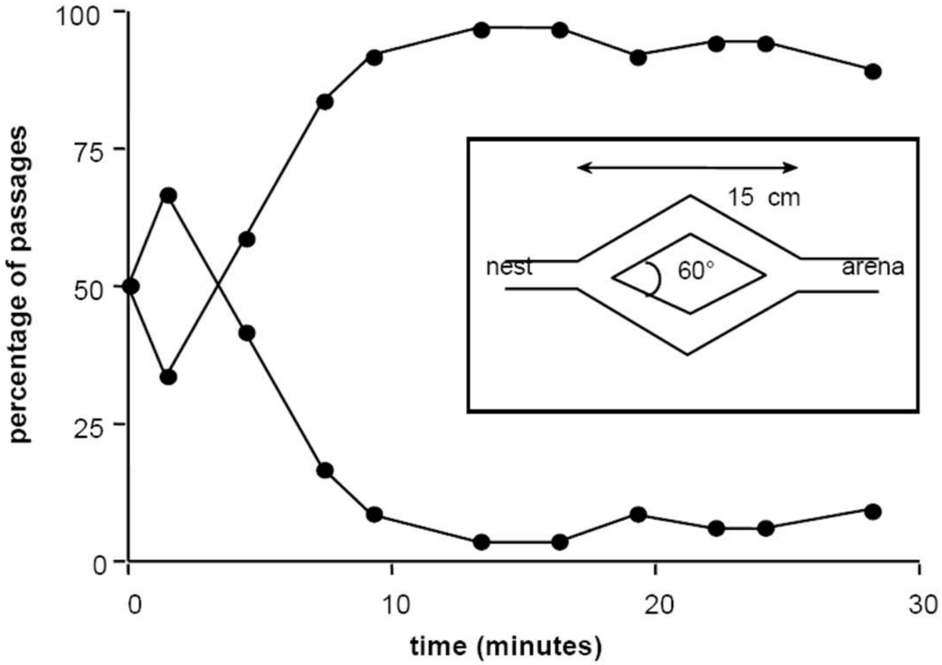


self-generated chemoattractant gradients allow cells to navigate complex paths with great efficiency. *Dictyostelium discoideum* cells (slime mold, which find each other over large distances in the environment) and metastatic cancer cells (which spread around the human body). Both successfully solved a range of complex mazes and identify optimum paths.

Tweedy, et al [2020]. "Seeing around Corners: Cells Solve Mazes and Respond at a Distance Using Attractant Breakdown." *Science* **369** (6507): eaay9792.

rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

stigmergy at work: ant colony optimization

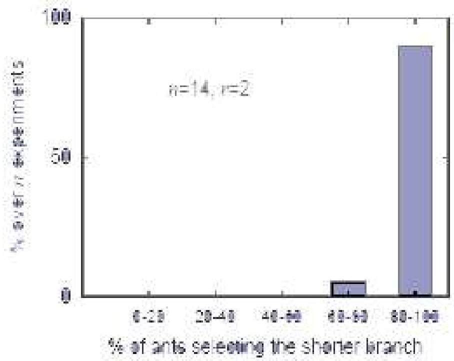


J.L. Deneubourg, S. Aron, S. Goss, J.M. Pasteels [1990] "The self-organizing exploratory pattern of the argentine ant". *Journal of Insect Behavior*.

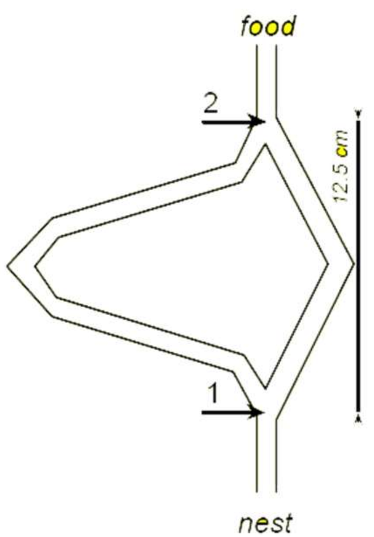
After an initial transitory phase lasting few minutes during which some oscillations can appear, ants tend to converge on the same path

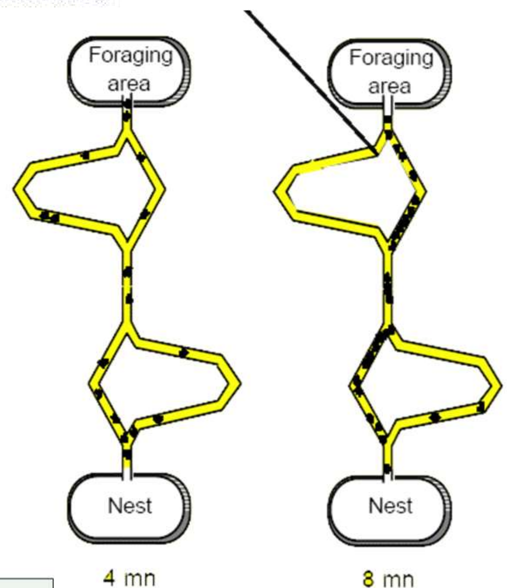
rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

stigmergy at work



S Goss, S Aron, JL Deneubourg, JM Pasteels [1989]. "Self-organized shortcuts in the Argentine ant". *Naturwissenschaften*, 76, pp. 579–581.

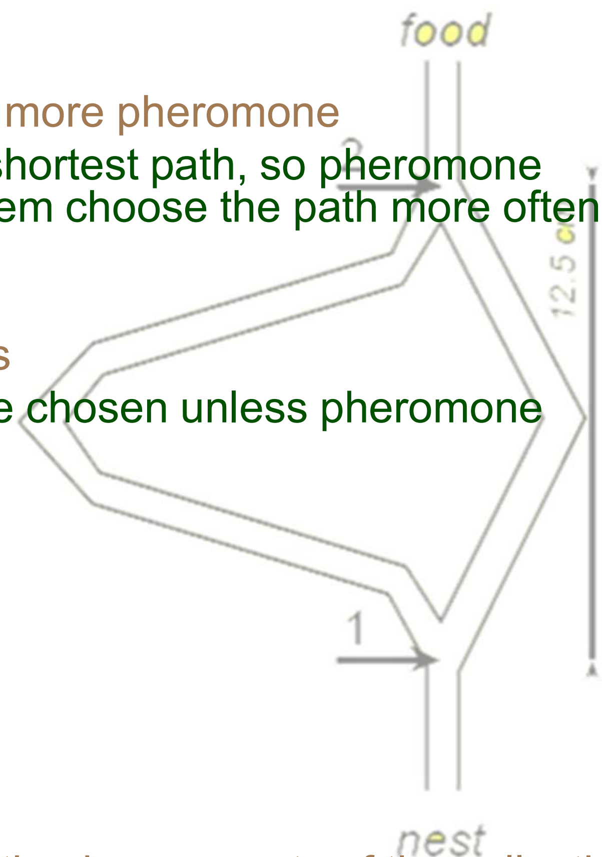




rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

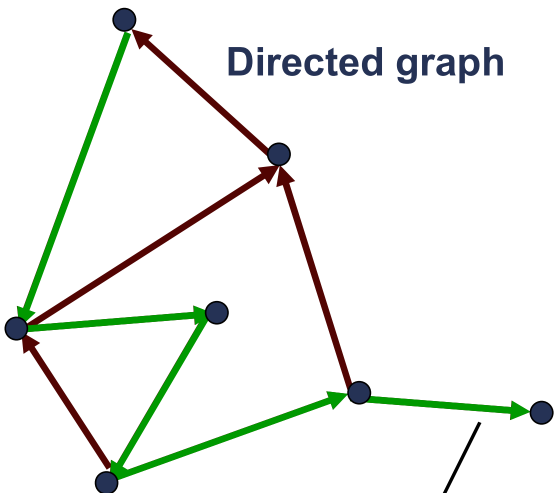
ant colony optimization

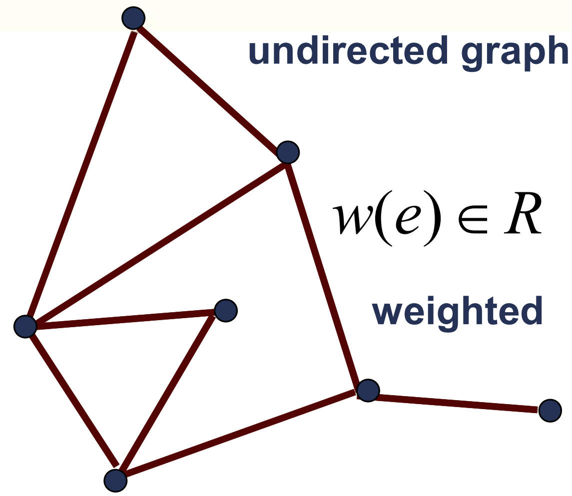
- Path optimization
  - Stigmergy
    - ***Reinforcement***: Shortest path contains probabilistically more pheromone
      - First ants to get to food source are those using the shortest path, so pheromone remains stronger in the whole path, which makes them choose the path more often when going back
  - Dependence on dynamic parameters (self-organization)
    - Pheromone evaporation, number of ants, length of paths
      - If shortest path is introduced much later, it will not be chosen unless pheromone evaporates very quickly
  - Pheromone release is proportional to food source quality
    - ***Exploitation*** of better sources
  - Ants wander off path with a certain probability
    - Random behavior necessary for ***exploration*** of space
  - Distributed search
    - Population of foraging ants
  - Collective Path Optimization (global coordination)
    - A single ant (one solution) cannot solve it, path optimization is a property of the collective



BINGHAMTON UNIVERSITY STATE UNIVERSITY OF NEW YORK
rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

basic definitions





Path: Sequence of vertex, edge, vertex, edge….

$$G = (\boxed{V}, \boxed{E})$$

Vertices

Edges

Adjacency Matrix

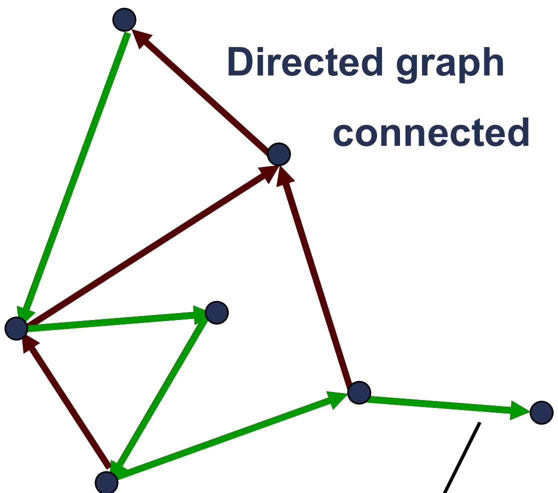
v_i (columns), v_j (rows)

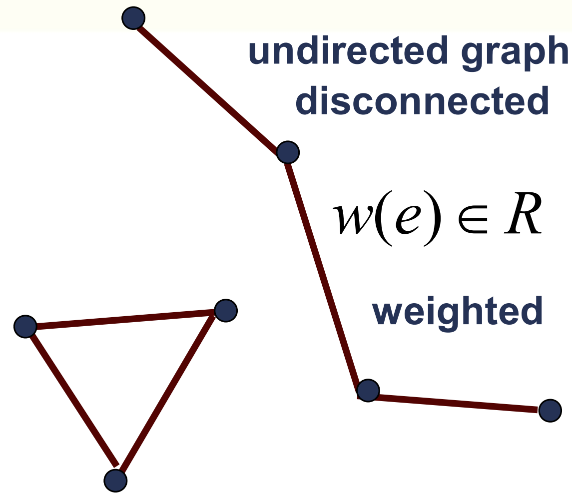
1	0.3	0.5	0.2	0.2
0.8	1	0.3	1.9	1
0.4	0.5	1	0.7	0.9
0.1	0.5	0.6	1	0.7
1	0.9	0.4	0.6	1

$$w(e_{i,j}) = 0.6$$

rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

basic definitions





$$G = (\boxed{V}, \boxed{E})$$

Vertices

Edges

Path: Sequence of vertex, edge, vertex, edge….

Adjacency Matrix

v_i (columns), v_j (rows)

1	0.3	0.5	0.2	0.2
0.8	1	0.3	1.9	1
0.4	0.5	1	0.7	0.9
0.1	0.5	0.6	1	0.7
1	0.9	0.4	0.6	1

$$w(e_{i,j}) = 0.6$$

rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

finding the shortest path

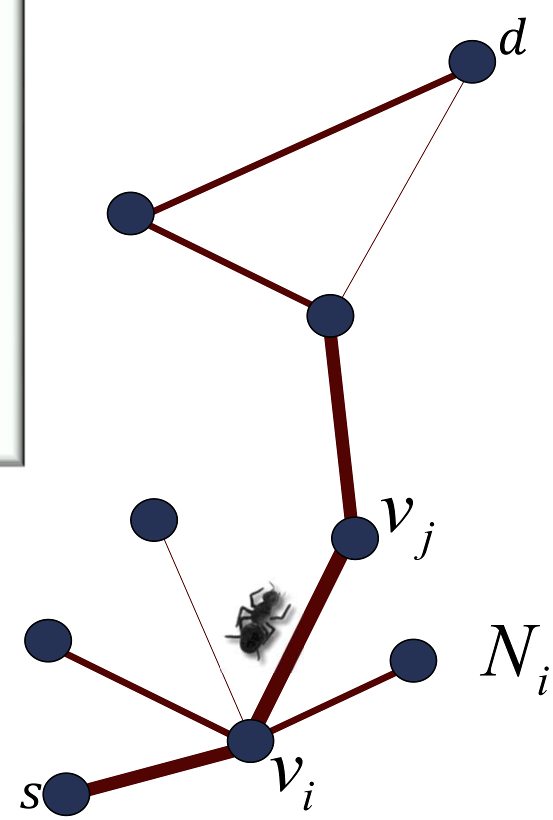
- Start with a weighted graph where edge weights are distances $d(e)$.
- A solution is a path from vertex s to vertex d
  - Length of path p is $\sum_{e \in p} d(e)$
- Pheromone level on edge $e_{i,j}$: $\tau_{i,j}$
- Pheromone evaporates
  - $\tau_{i,j}(t+1) = (1\text{-}\rho)\, \tau_{i,j}(t)$
- Population of artificial ants
  - Ant z traverses an edge (or path) at each iteration t
  - Releases pheromone every time it traverses an edge: $\Delta\tau$
  - Chooses next edge/path (v_j) to traverse after reaching vertex v_i:

Collective signal

$$p_{i,j}^{z} = \frac{\boxed{\left(\tau_{i,j}\right)^{a}}\boxed{\left(d_{i,j}\right)^{-b}}}{\sum_{\boxed{k \in N_i}} \left[\left(\tau_{i,k}\right)^{a}\left(d_{i,k}\right)^{-b}\right]}$$

Desirability, distance, or visibility

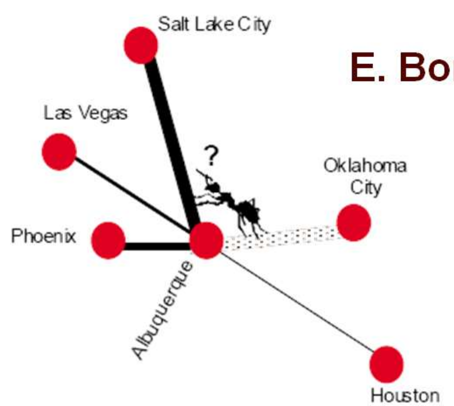
Alternative edges/paths



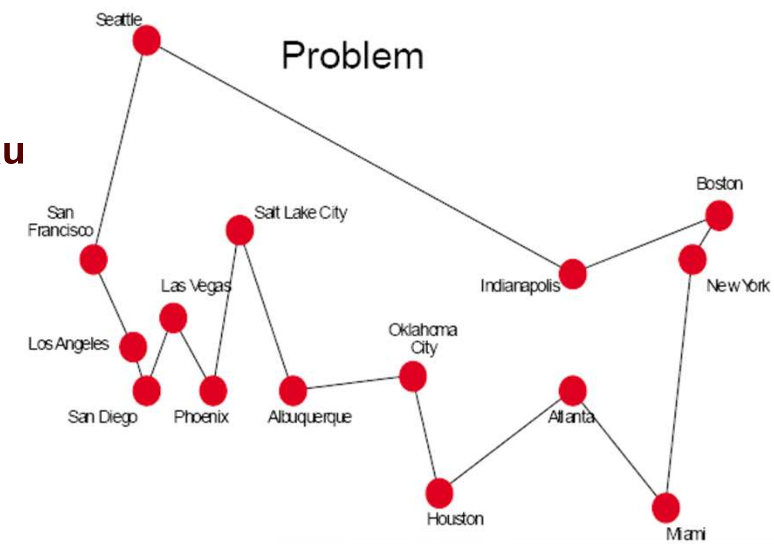
BINGHAMTON UNIVERSITY STATE UNIVERSITY OF NEW YORK
rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

ant colony optimization

- d_{ij}= distance between city i and city j
- τ_{ij}= virtual pheromone on edge(i,j)
- m agents, each building a tour
  - At each step of a tour, the probability to go from city i to city j is proportional to $(\tau_{ij})^a(d_{ij})^{-b}$
  - After building a tour of length L, each agent reinforces the edges is has used by an amount proportional to $1/L$
- The virtual pheromone evaporates: $\tau \rightarrow (1-\rho)\ \tau$



E. Bonabeau



BINGHAMTON UNIVERSITY STATE UNIVERSITY OF NEW YORK
rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

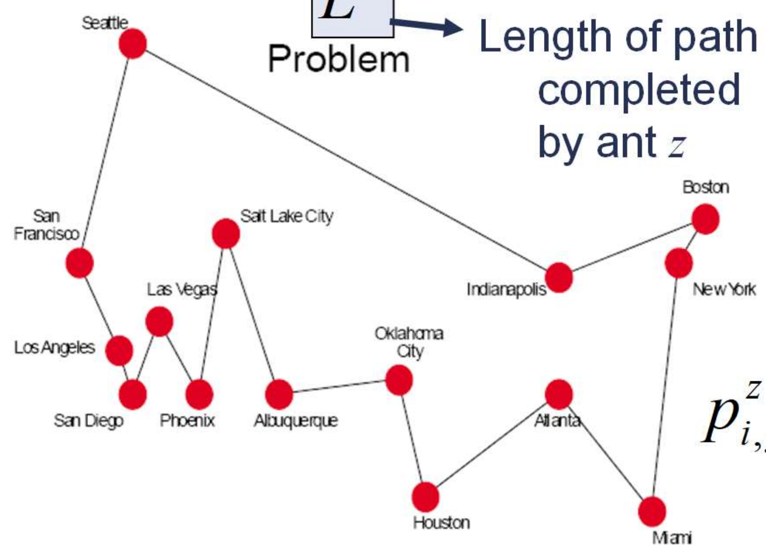
For the traveling salesman problem

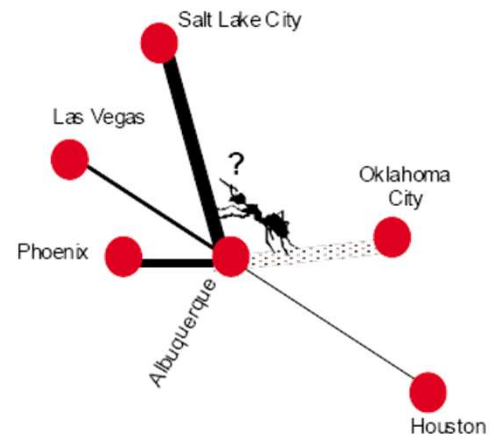
- Pheromone release proportional to quality of solution

$$\Delta\tau_{i,j}^{z} = \frac{C}{\boxed{L^{z}}}$$

Problem

Length of path completed by ant z





$$p_{i,j}^{z} = \frac{\left(\tau_{i,j}\right)^{a}\left(d_{i,j}\right)^{-b}}{\sum_{k\in N_i}\left[\left(\tau_{i,k}\right)^{a}\left(d_{i,k}\right)^{-b}\right]}$$

Dorigo M. & L.M. Gambardella (1997). Ant Colonies for the Traveling Salesman Problem. *BioSystems,* 43:73-81.

Box pushing tasks

Taxis-based action (reflex translation or rotation in response to stimulus) and *kinesthetic*-based action (or proprioception)

+ *realignment* and *repositioning*

C. Ronald Kube, Chris A. Parker, Tao Wang and Hong Zhang. "Biologically Inspired Collective Robotics," Chapter 15 in *Recent Developments in Biologically Inspired Computing*, de Castro, Leandro N. and Von Zuben, Fernando J., editors, Idea Group Publlishing, 456 pages, 2005.

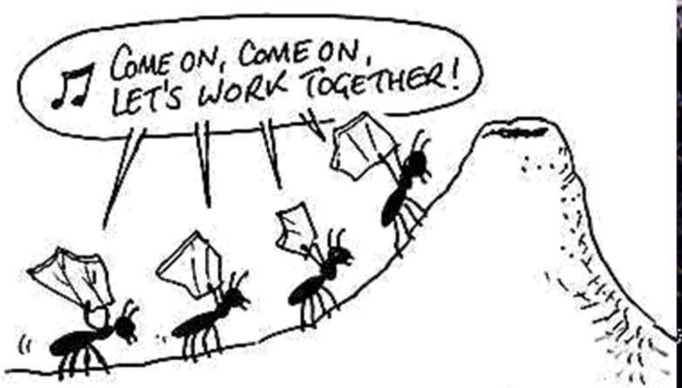
rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

From Guy Theraulaz

Typical tasks for social insects: find appropriate place to build nest, build and maintain nest, task allocation,feed colony, find food, respond to challenges, send an alarm, etc.

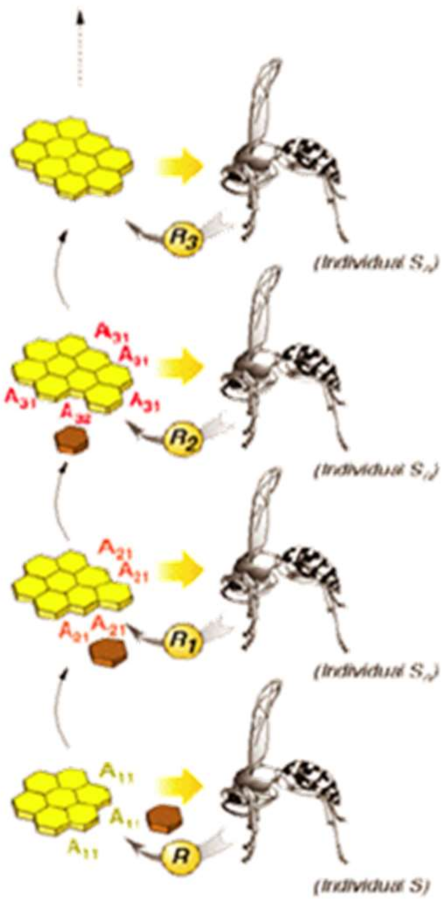
rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

natural organization



rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

by stigmergy

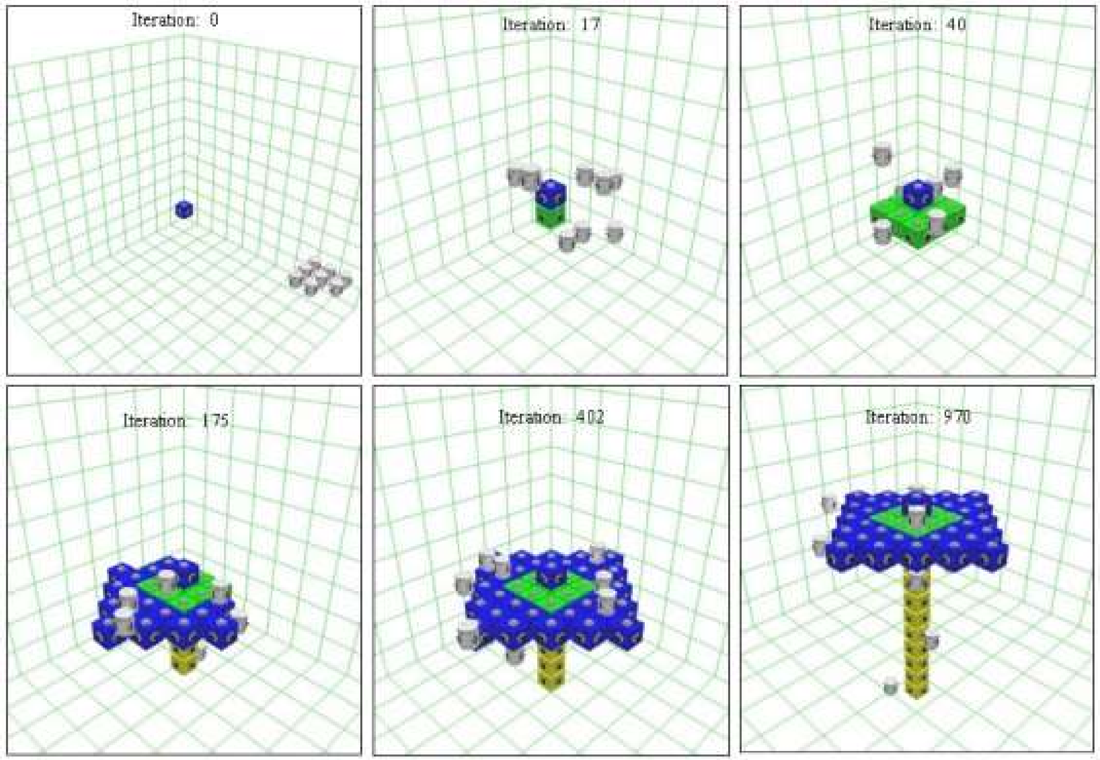


From E. Bonabeau. "Swarm Intelligence".

- Self-assembly algorithm
  - Agents move randomly on a 3D grid of sites.
  - An agent deposits a brick every time it finds a ***stimulating configuration***.
    - Rule table contains all such configurations
  - A rule table defines a particular self-assembly algorithm.
    - Rule space is very large

BINGHAMTON UNIVERSITY STATE UNIVERSITY OF NEW YORK
rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

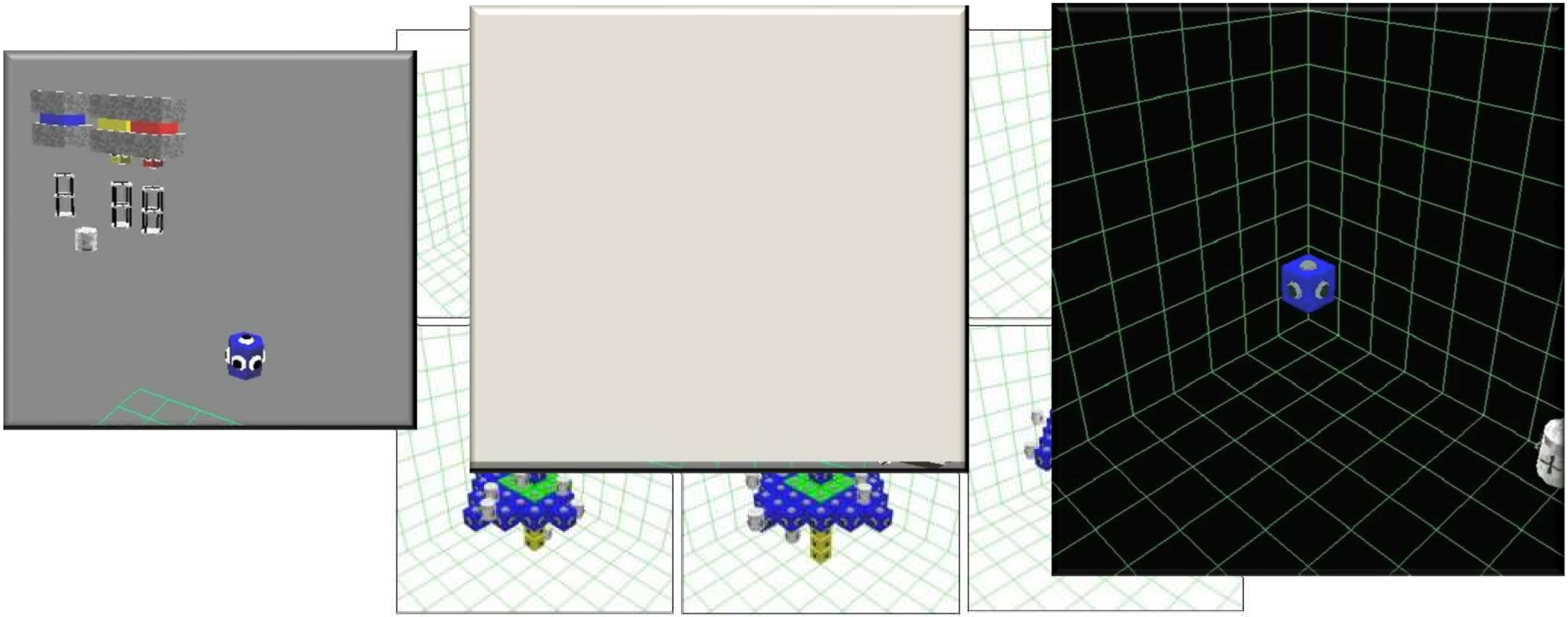
"space-station" by dynamic concepts (dynamic-concepts.com)



Phase 1: Simulating construction rules

rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

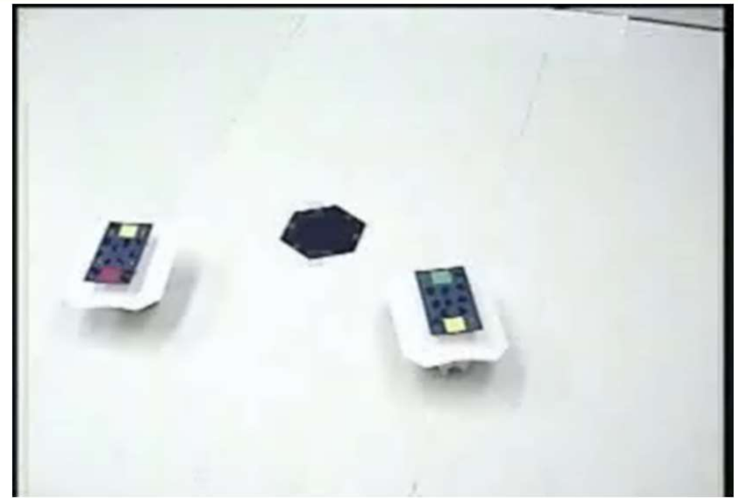
"space-station" by dynamic concepts (dynamic-concepts.com)

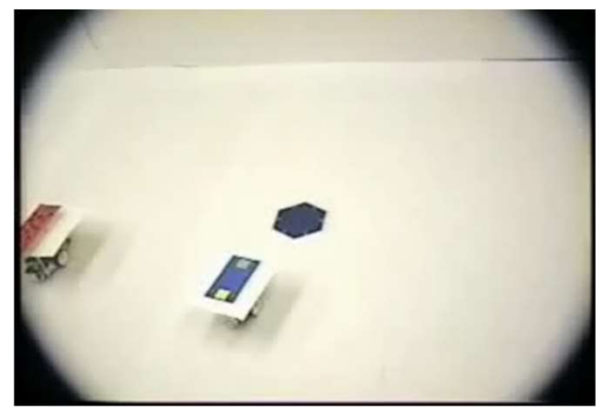


Phase 1: Simulating construction rules

rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

by dynamic concepts (phase two)

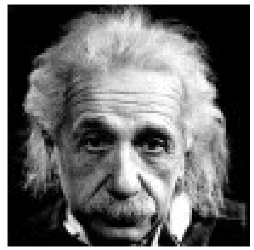


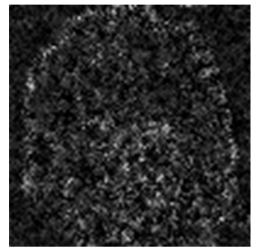


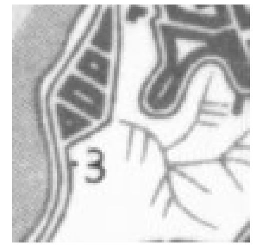
Phase 2: prototype robots

rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

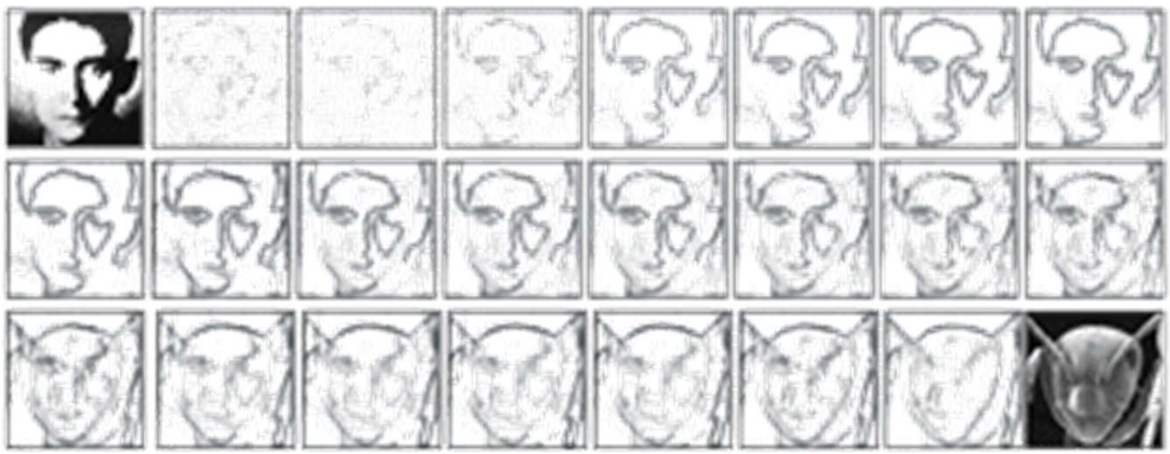
Vitorino Ramos: Pheromone Fields as Swarm Cognitive Maps





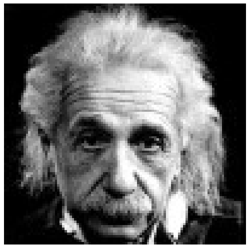


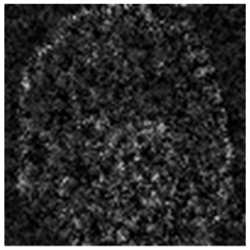
Artificial Ants in Digital Image Habitats

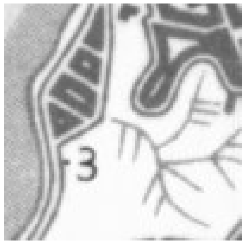


rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

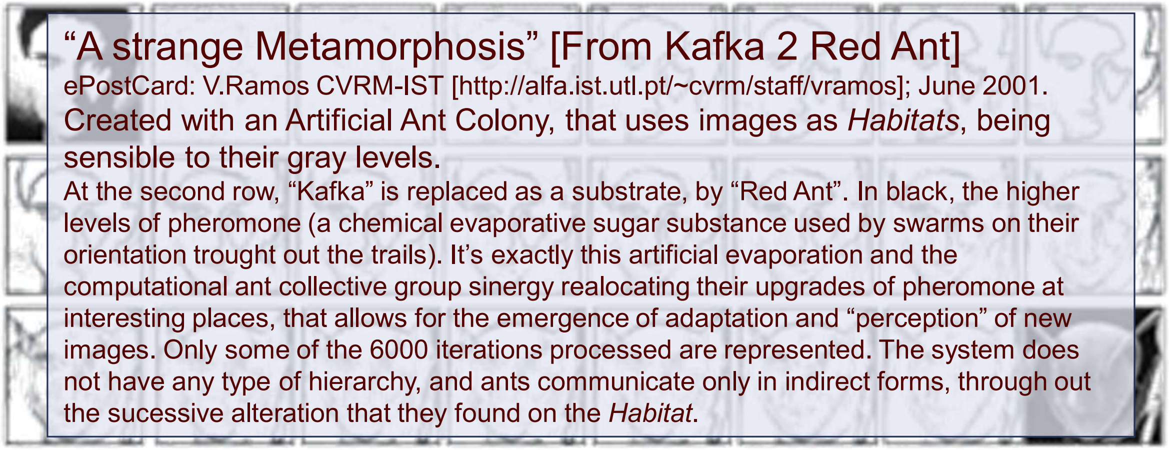
Vitorino Ramos: Pheromone Fields as Swarm Cognitive Maps







Artificial Ants in Digital Image Habitats



“A strange Metamorphosis” [From Kafka 2 Red Ant]

ePostCard: V.Ramos CVRM-IST [http://alfa.ist.utl.pt/~cvrm/staff/vramos]; June 2001.

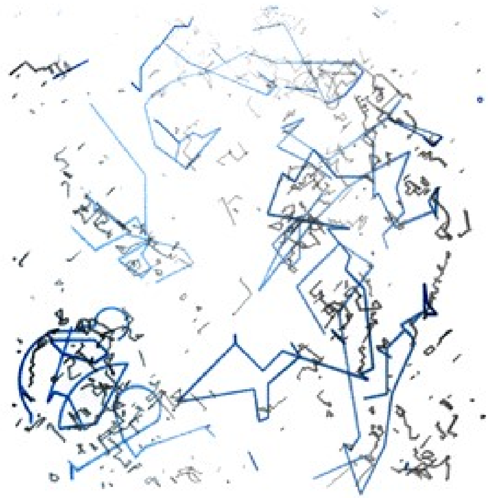
Created with an Artificial Ant Colony, that uses images as *Habitats*, being sensible to their gray levels.

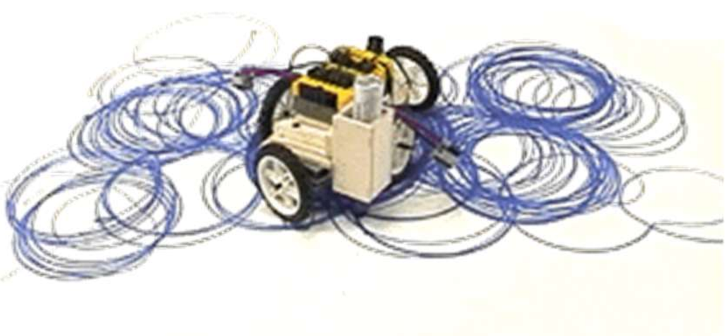
At the second row, “Kafka” is replaced as a substrate, by “Red Ant”. In black, the higher levels of pheromone (a chemical evaporative sugar substance used by swarms on their orientation trought out the trails). It’s exactly this artificial evaporation and the computational ant collective group sinergy realocating their upgrades of pheromone at interesting places, that allows for the emergence of adaptation and “perception” of new images. Only some of the 6000 iterations processed are represented. The system does not have any type of hierarchy, and ants communicate only in indirect forms, through out the sucessive alteration that they found on the *Habitat*.

rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

swarm art

Leonel Moura



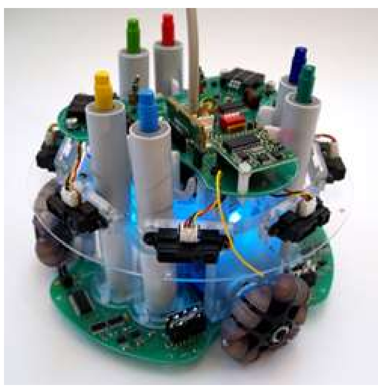


rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

Leonel Moura's RAP (Robotic Action Painter)

@ The American Museum of Natural History


Skeptical Inquirer
Special Issue
THE MAGAZINE FOR SCIENCE AND REASON
SCIENCE + ART
Steven Pinker Humanities and Human Nature
Does Skepticism Kill Creativity?
Galileo Meets Matisse
Why We Read Fiction
Spectral Music
The Neurobiology of the Beholder
The Color Palette of the Cosmos

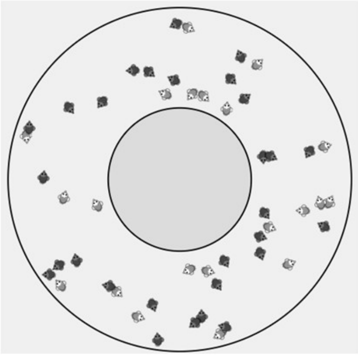


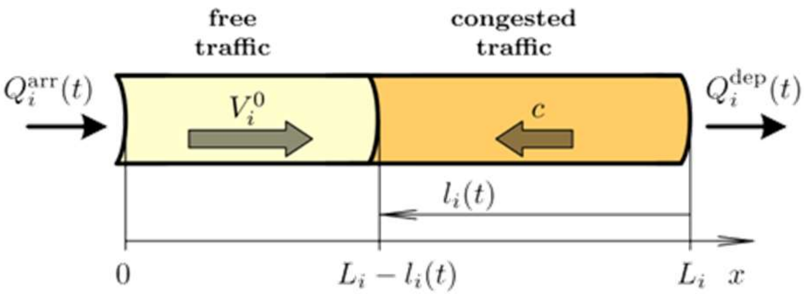
- sensors
  - to avoid obstacles, to perceive the presence of visitors near the case, to check the paper, and most important to detect color.
- Two modes
  - Random until color threshold is detected.
    - Random sketching
    - Random seed from relative direction measured by an onboard compass.
  - Reactive After passing color threshold
    - Does not go back
    - Draws only where color exceeds threshold.
- Stopping criteria
  - Pattern in color sensor grid
  - signs off at the corner and flashes lights

rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

Humans as particle systems

- Vehicles and people modeled as particles in a fluid medium
  - Free traffic: behaves as a gas
    - Particles move freely
  - Congested traffic: behaves as a liquid
    - movement of particles strongly depends on surrounding dynamics
  - Shock waves
    - emerge from density variations
    - Example in congested traffic
      - The velocity change of a vehicle propagates (with a homogenous time delay) in the opposite direction of traffic as downstream vehicle respond to changes in upstream vehicles
      - propagation speed aprox. -15 km/h (In free traffic = free vehicle velocity).



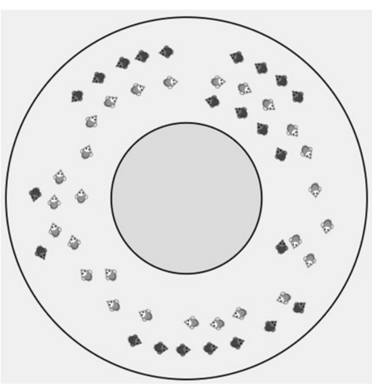


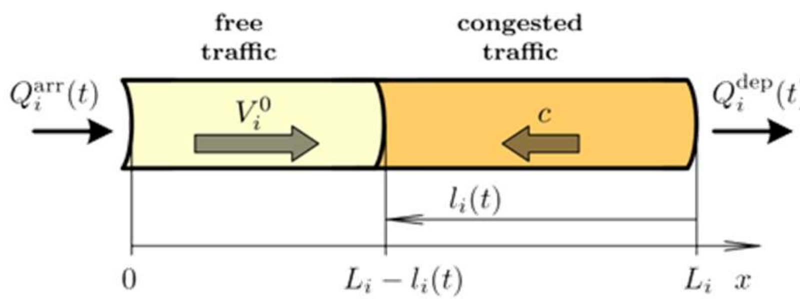
D. Helbing: Traffic and related self-driven many-particle systems. *Reviews of Modern Physics* **73**, 1067-1141 (2003).

complexity-explorables.org: the-walking-head\

Humans as particle systems

- Vehicles and people modeled as particles in a fluid medium
  - Free traffic: behaves as a gas
    - Particles move freely
  - Congested traffic: behaves as a liquid
    - movement of particles strongly depends on surrounding dynamics
  - Shock waves
    - emerge from density variations
    - Example in congested traffic
      - The velocity change of a vehicle propagates (with a homogenous time delay) in the opposite direction of traffic as downstream vehicle respond to changes in upstream vehicles
      - propagation speed aprox. -15 km/h (In free traffic = free vehicle velocity).





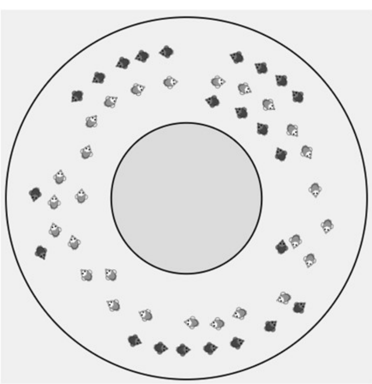
D. Helbing: Traffic and related self-driven many-particle systems. *Reviews of Modern Physics* **73**, 1067-1141 (2003).

complexity-explorables.org: the-walking-head\

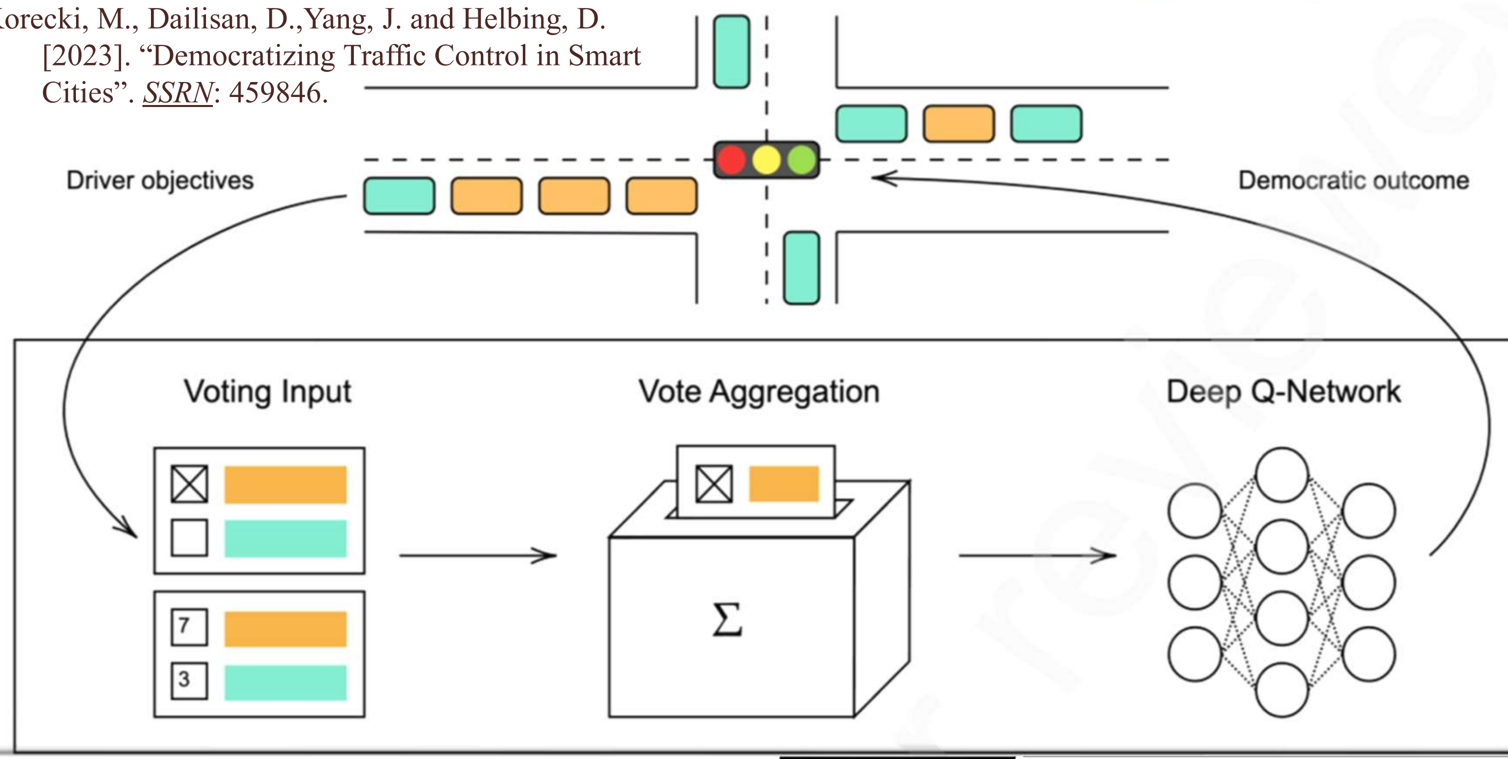
rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

Humans as particle systems

- Vehicles and people modeled as particles in a fluid medium
  - Free traffic: behaves as a gas
    - Particles move freely
  - Congested traffic: behaves as a liquid
    - movement of particles strongly depends on surrounding dynamics
  - Shock waves
    - emerge from de
    - Example in con
      - The velocity delay) in the to changes i
      - propagation



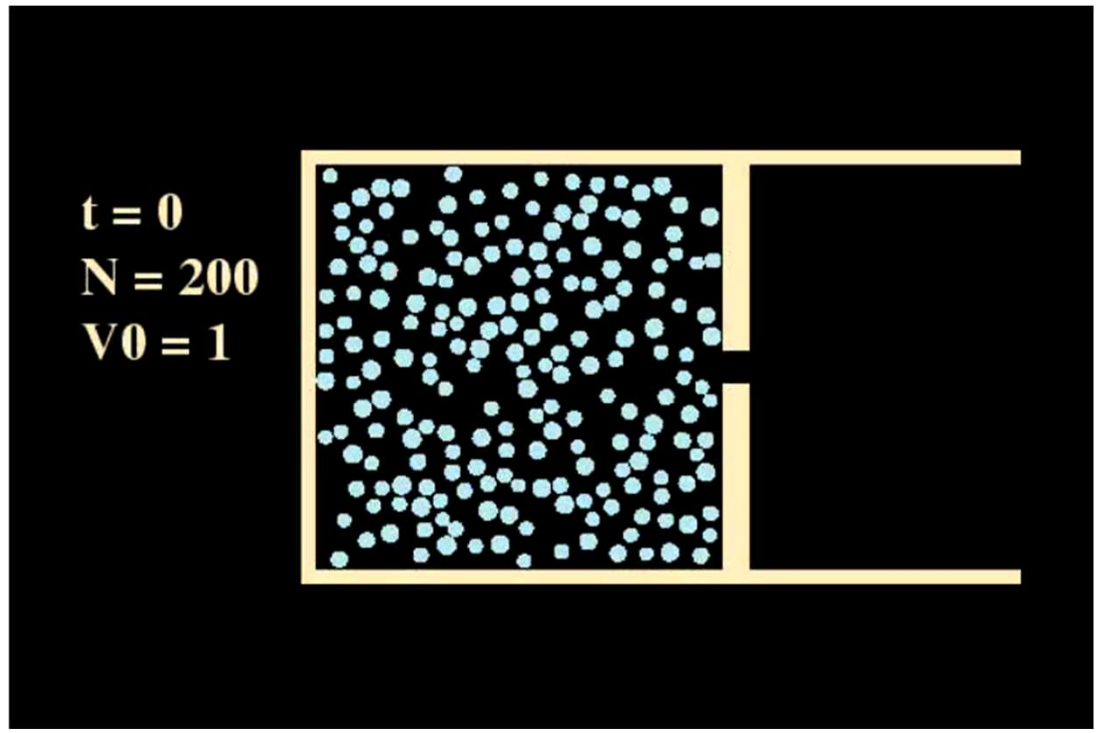
Korecki, M., Dailisan, D.,Yang, J. and Helbing, D. [2023]. “Democratizing Traffic Control in Smart Cities”. SSRN: 459846.



complexity-explorables.org: the-walking-

Dirk Helbing's Group

- People modeled as self-driven many-particle systems
- Testing individualistic vs herding behavior as well as environmental solutions



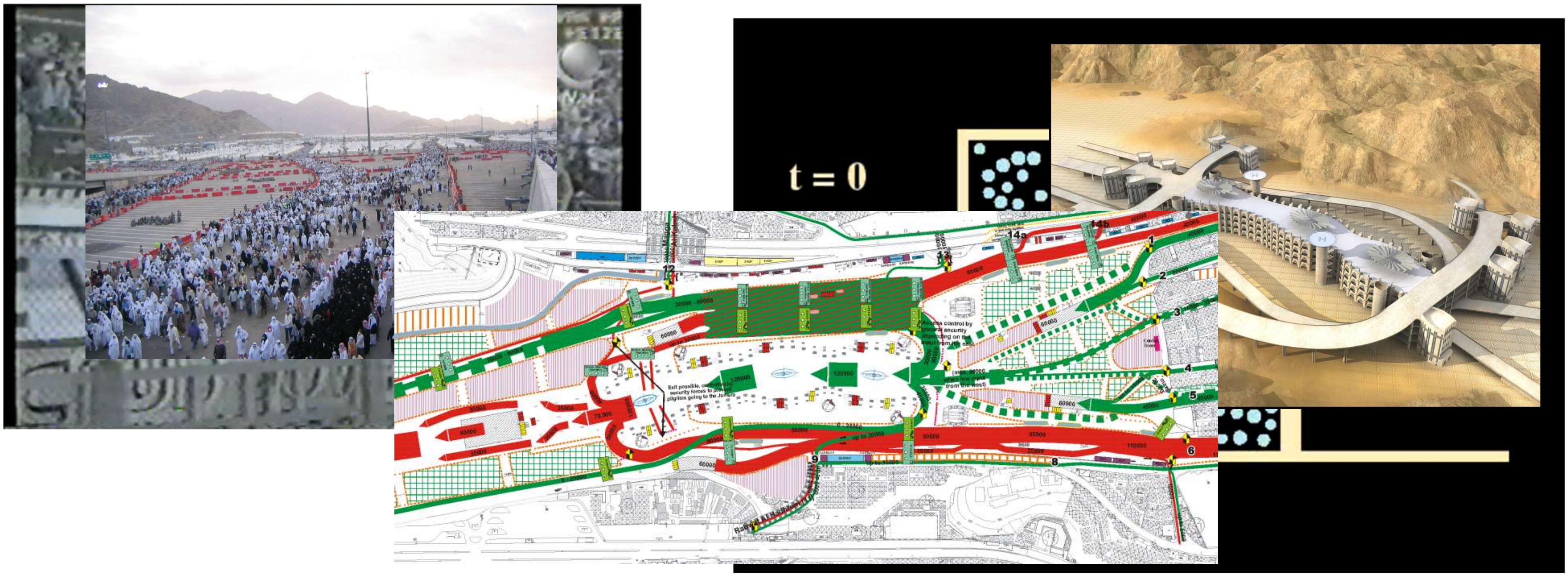
D. Helbing, A. Johansson and H. Z. Al-Abideen (2007) The Dynamics of Crowd Disasters: An Empirical Study. *Physical Review E* 75, 046109.

BINGHAMTON UNIVERSITY
STATE UNIVERSITY OF NEW YORK
rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

Modeling crowd disasters

Dirk Helbing's Group

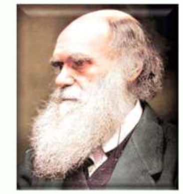
- People modeled as self-driven many-particle systems
- Testing individualistic vs herding behavior as well as environmental solutions



D. Helbing, A. Johansson and H. Z. Al-Abideen (2007) The Dynamics of Crowd Disasters: An Empirical Study. *Physical Review E* 75, 046109.

readings

- Class Book
  - Floreano, D. and C. Mattiussi [2008]. *Bio-Inspired Artificial Intelligence: Theories, Methods, and Technologies*. MIT Press.
    - **Chapter 5**



- Lecture notes
  - Chapter 1: What is Life?
  - Chapter 2: The logical Mechanisms of Life
  - Chapter 3: Formalizing and Modeling the World
  - Chapter 4: Self-Organization and Emergent Complex Behavior
  - Chapter 5: Reality is Stranger than Fiction
  - Chapter 6: Von Neumann and Natural Selection
  - Chapter 7: Modeling Evolutionary Systems
    - posted online @ casci.binghamton.edu/academics/i-bic
- Papers and other materials
  - Optional
    - Nunes de Castro, Leandro [2006]. *Fundamentals of Natural Computing: Basic Concepts, Algorithms, and Applications*. Chapman & Hall.
      - Chapter 5, 7.7, 8.3.1, 8.3.6,

rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic