C. Slime Mold

*Dictyostelium discoideum*  
“Dicty”

Self-organization in Bio-inspired Robotics


Self-copying Robot (2005)

- Hod Lipson, Cornell
- Programmable blocks
- 2 swiveling pyramidal halves
- Magnetic connections
- 10 cm across
- One stack can assemble another

Amoeba Stage

- Single cell
- Lives in soil
- Free moving
- Engulfs food (bacteria)
- Divides asexually

Amoebas
Aggregation Stage

- Triggered by exhaustion of food
- Aggregate by chemotaxis
- Form expanding concentric rings and spirals
- Up to 125,000 individuals

Spiral Waves

- Spiral accelerate cell aggregation (18 vs. 3 $\mu$m/min.)
- Waves propagate 120 – 60 $\mu$m/min.
- 1 frame = 36 sec.

Center of Spiral

- Mechanisms of spiral formation are still unclear
- Involves symmetry breaking
- 1 frame = 10 sec.

Stream Formation Stage

- Streams result from dependence of wave propagation velocity on cell density
- Breaks symmetry
- As density increases, begin to adhere
- Begin to form mound

Mound Stage

- Cells differentiate
- Some form an elongated finger

Concentric Waves in Mounds

- Concentric or spiral waves
- Mound comprises $10^3$ to $10^5$ cells
- Cells begin to differentiate
- 1 frame = 20 sec.
Part 2C: Slime Mold

Multiple Centers

- Multiple pacemakers
- Wave fronts mutually extinguish (typical of excitable media)
- One center eventually dominates

Multi-armed Spirals

- This mound has 5 spiral arms
- Up to 10 have been observed

Formation of Acellular Sheath

- Composed of cellulose & a large glycoprotein
- Covers mound and is left behind slug as trail
- Function not entirely understood:
  - protection from nematodes (worms)
  - control of diffusion of signaling molecules

Slug Stage

- Prestalk elongates, topples, to form slug
- Behaves as single organism with $10^5$ cells
- Migrates; seeks light; seeks or avoids heat
- No brain or nervous system

Movement of Young Slug

- Time-lapse (1 frame = 10 sec.)
- Note periodic up-and-down movement of tip

Movement of Older Slug

- Note rotating prestalk cells in tip
- Pile of anterior-like cells on prestalk/prespore boundary
- Scale bar = 50 µm, 1 frame = 5 sec.
Part 2C: Slime Mold

Migration of Older Slug

- Scale bar = 100 µm, 1 frame = 20 sec.

Culmination Stage

- Cells differentiate into base, stalk, and spores
- Prestalk cells form rigid bundles of cellulose & die
- Prespore cells (at end) cover selves with cellulose & become dormant

Stages of Culmination

Cell Differentiation at Culmination

- Video: Zool. Inst., Univ. München

Early Culmination

- During early culmination all cell in prestalk rotate
- Scale bar = 50 µm, 1 frame = 25 sec.

Late Culmination

- Vigorous rotation at prestalk/prespore boundary
- Scale bar = 100 µm, 1 frame = 10 sec.
Part 2C: Slime Mold

Fruiting Body Stage

- Spores are dispersed
- Wind or animals carry spores to new territory
- If sufficient moisture, spores germinate, release amoebas
- Cycle begins again

Cooperation and Altruism in Dicty

- Cooperation is essential to Dicty signaling and aggregation
- “Altruism” is essential in stalk formation
- How is cooperation encouraged and cheating discouraged?
- In one case the same gene prevents cheating and allows cohesion
- Green-beard genes?

Microbial Cooperation and Altruism

Slime Mold Solving Maze

- Different slime mold: Physarum polycephalum
- Lengths: α1 (41mm), α2 (33), β1 (44), β2 (45)
- AG = food sources
  (a) initial, (b) exploring possible connections (4 hrs), (c) shortest (4 more)

Slime Mold-Controlled Robot

- Robot sensors relayed to remote computer
- Light shined on slime mold
- Slime mold retracts
- Motion tracked and used to control robot
- Physarum polycephalum
Emergent Patterns During Aggregation

- a-c. As aggregate, wave lengths shorten
- d. Population divides into disjoint domains
- e-f. Domains contract into “fingers” (streaming stage)

Belousov-Zhabotinski Reaction

Hodgepodge Machine

Demonstration of Hodgepodge Machine

- Run NetLogo B-Z Reaction Simulator
- Run Hodgepodge simulator at CBN
  Online Experimentation Center
  <mitpress.mit.edu/books/Fractal/chn/chn/html/java.html>

Universal Properties

- What leads to these expanding rings and spirals in very different systems?
- Under what conditions do these structures form?
- What causes the rotation?
- These are all examples of excitable media

Reading

- Read Flake, ch. 18