C.
Slime Mold

(*Dictyostelium discoideum*)
"Dicty"

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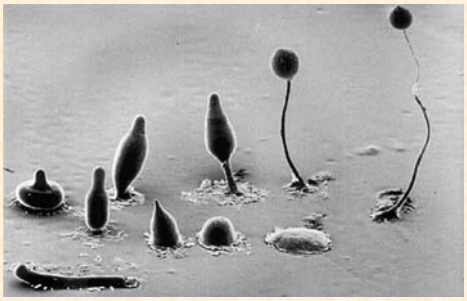
Complete Life Cycle



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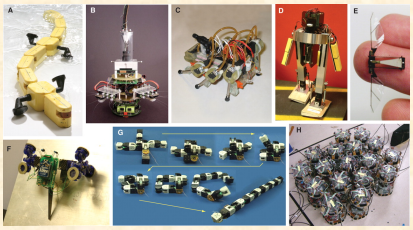
Self-organization in Bio-inspired Robotics



R. Pfeifer et al., Science 318, 1088 -1093 (2007)

Science AAAS

2013/2/4
Published by AAAS

3

Self-copying Robot (2005)

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

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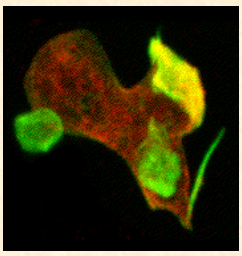
Amoeba Stage



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

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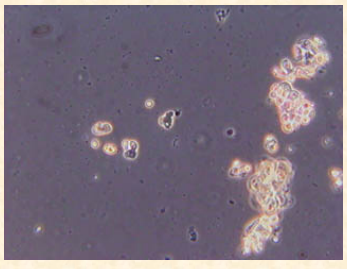
Amoebas



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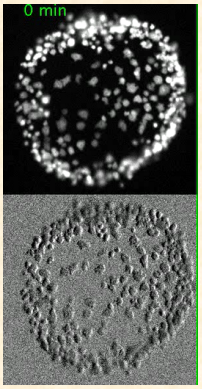


Aggregation Stage

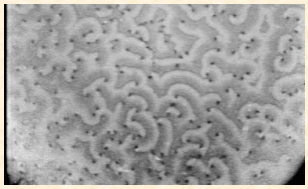
- Triggered by exhaustion of food
- Aggregate by *chemotaxis*
- Example: 180 cells
- Time lapse: about 14 hours

Science 21 May 2010: Vol. 328, 1021–1025

Aggregation Stage

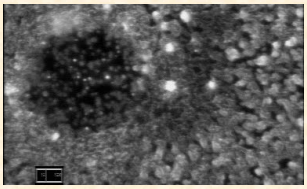
- Triggered by exhaustion of food
- Aggregate by *chemotaxis*
- Form expanding concentric rings and spirals
- Up to 125 000 individuals

Spiral Waves



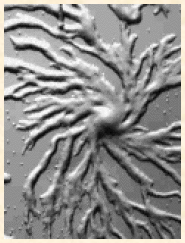
- Spiral accelerate cell aggregation (18 vs. 3 μm/min.)
- Waves propagate 120 – 60 μm/min.
- 1 frame = 36 sec.

Center of Spiral



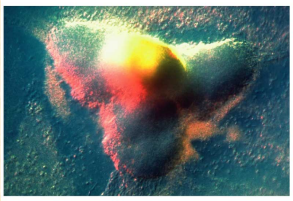
- Mechanisms of spiral formation are still unclear
- Involves symmetry breaking
- 1 frame = 10 sec.

Stream Formation Stage



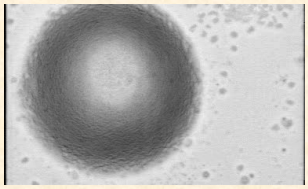
- Streams result from dependence of wave propagation velocity on cell density
- Breaks symmetry
- As density increases, begin to adhere
- Begin to form *mound*

Mound Stage



- Cells differentiate
- Some form an elongated finger

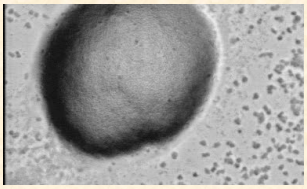
Concentric Waves in Mounds



- Concentric or spiral waves
- Mound comprises 10^3 to 10^5 cells
- Cells begin to differentiate
- 1 frame = 20 sec.

2013/2/4 (video < Zool. Inst., Univ. München) 13

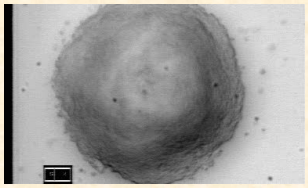
Multiple Centers



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

2013/2/4 (video < Zool. Inst., Univ. München) 14

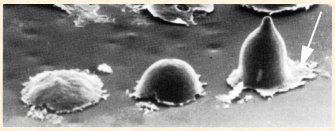
Multi-armed Spirals



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

2013/2/4 (video < Zool. Inst., Univ. München) 15

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

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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

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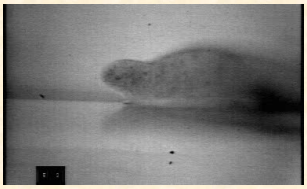
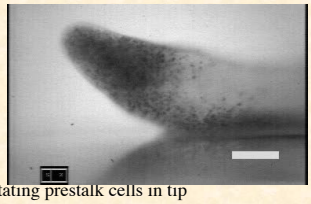
Movement of Young Slug



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

2013/2/4 (video < Zool. Inst., Univ. München) 18

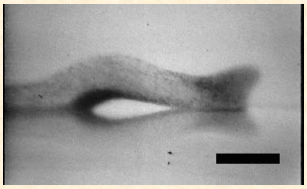
Movement of Older Slug



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

2013/2/4 (video < Zool. Inst., Univ. München) 19

Migration of Older Slug



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

2013/2/4 (video < Zool. Inst., Univ. München) 20

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

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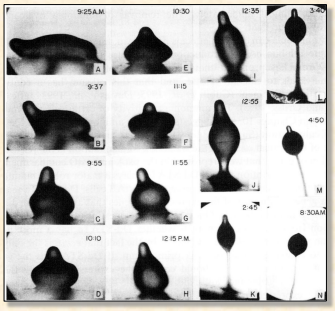
Stages of Culmination



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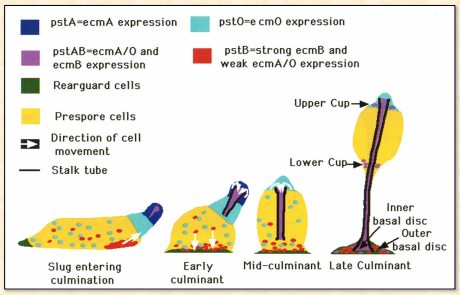
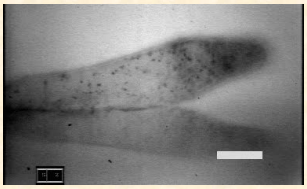
Cell Differentiation at Culmination



2013/2/4 (figure from Kessin, *Dictyostelium*) 23

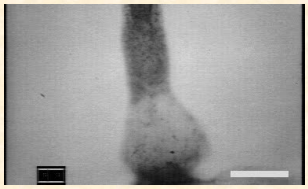
Early Culmination



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

2013/2/4 (video < Zool. Inst., Univ. München) 24

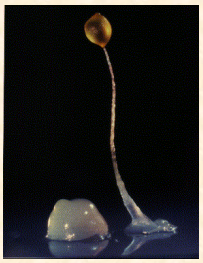
Late Culmination



- Vigorous rotation at prestalk/prespore boundary
- Scale bar = 100 μm, 1 frame = 10 sec.

2013/2/4 (video < Zool. Inst., Univ. München) 25

Fruiting Body Stage



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

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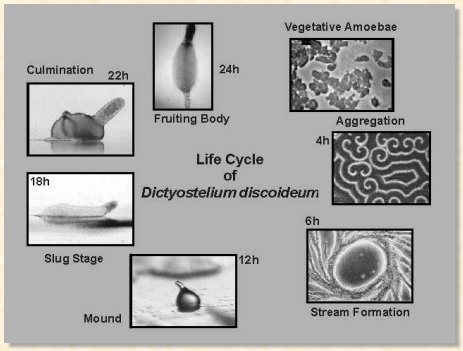

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Cooperation and Altruism in Dicty

- 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?

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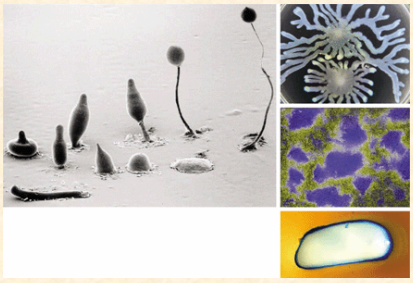
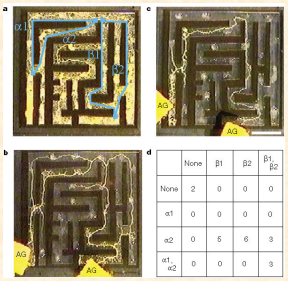
Microbial Cooperation and Altruism



Published by AAAS E. Pennisi Science 325, 1196-1199 (2009)

Science AAAS

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)

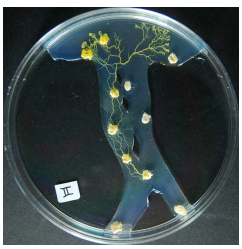
2013/2/4 [fig. < Nakagaki, Yamada & Tóth, *Nature* **407**, 470 (28 September 2000)] 30

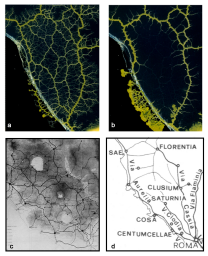
Slime Mold-Controlled Robot

- Robot sensors relayed to remote computer
- Light is shined on slime mold
- Slime mold retracts
- Motion tracked and used to control robot
- *Physarum polycephalum*

2013/2/4 (Klaus-Peter Zauner, University of Southampton, UK, 2006) 31

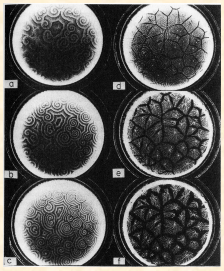
Slime Mold Computation of Roman Road Network





2013/2/4 Strano, Adamatzky & Jones, *Int. J. Nanotech. & Mol. Comp.*, in press 32

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)

2013/2/4 fig. from Solé & Goodwin 33

Belousov-Zhabotinski Reaction

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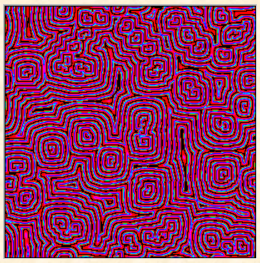
Hodgepodge Machine



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Demonstration of Hodgepodge Machine

Run NetLogo B-Z Reaction Simulator

or

Run Hodgepodge simulator at CBN Online Experimentation Center

<mitpress.mit.edu/books/FLAOH/cbnhtml/java.html>

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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

2D