

## C. Slime Mold

(*Dictyostelium discoideum*)  
“Dicty”

2/9/16

1

### Complete Life Cycle

2/9/16

2

### Self-organization in Bio-inspired Robotics

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

2/9/16  
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

2/9/16

4

### Dicty Videos

- [Bonner's videos](#)
- [Aggregation](#)
- [Life cycle](#)

2/9/16

5


### Amoeba Stage

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

2/9/16

6

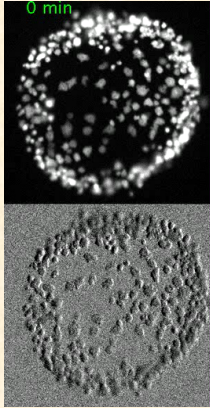
### Amoebas



A micrograph showing several amoebas, some of which are clustered together. The amoebas appear as small, irregularly shaped organisms with visible internal structures.

29/16 7

### Aggregation Stage




Two images showing the aggregation stage. The top image is a bright-field micrograph of a circular aggregate of cells, labeled "0 min". The bottom image is a phase-contrast micrograph of a similar aggregate.

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

Science 21 May 2010; Vol.328, 1021-1025  
8

29/16 8

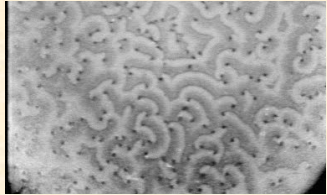
### Aggregation Stage



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

29/16 9

### Spiral Waves

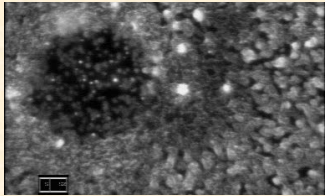


- Spiral accelerate cell aggregation (18 vs. 3  $\mu\text{m}/\text{min}$ .)
- Waves propagate 120–60  $\mu\text{m}/\text{min}$ .
- 1 frame = 36 sec.

(video < Zool.Inst., Univ. MÜNCHEN)

29/16 10

### Center of Spiral

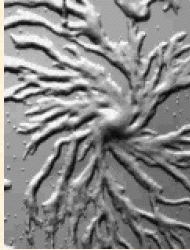


- Mechanisms of spiral formation are still unclear
- Involves symmetry breaking
- 1 frame = 10 sec.

(video < Zool.Inst., Univ. MÜNCHEN)

29/16 11

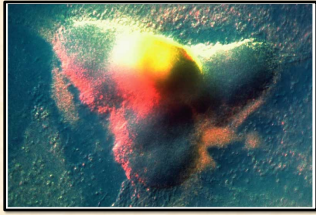
### Stream Formation Stage



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

29/16 12

### Mound Stage

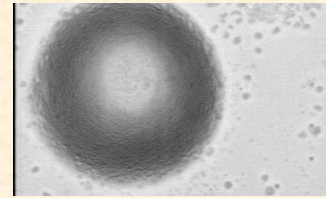


- Cells differentiate
- Some form an elongated finger

2/9/16

13

### Concentric Waves in Mounds



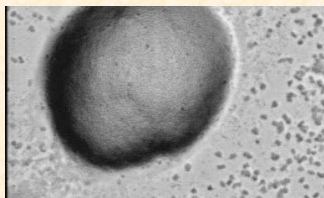
- Concentric or spiral waves
- Mound comprises  $10^3$  to  $10^5$  cells
- Cells begin to differentiate
- 1 frame = 20 sec.

2/9/16

(video &lt; Zool.Inst., Univ. München)

14

### Multiple Centers



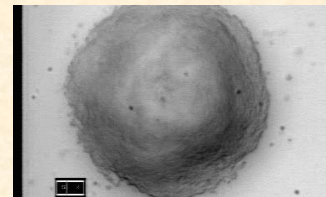
- Multiple pacemakers
- Wave fronts mutually extinguish (typical of excitable media)
- One center eventually dominates

2/9/16

(video &lt; Zool.Inst., Univ. München)

15

### Multi-armed Spirals



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

2/9/16

(video &lt; Zool.Inst., Univ. München)

16

### Formation of Acellular Sheath

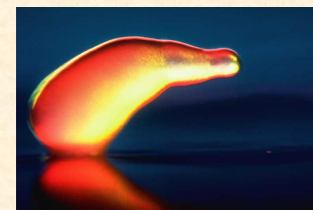


- Composed of cellulose & a large glycoprotein
- Covers mound and is left behind slug as trail
- Function not entirely understood:
  - protection from nematodes (worms)
  - control of diffusion of signaling molecules

2/9/16

17

### Slug Stage

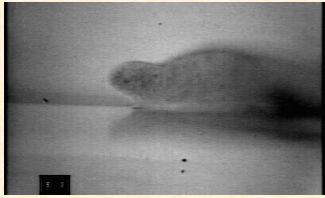


- Prestalk elongates, topples, to form slug
- Behaves as single organism with  $10^5$  cells
- Migrates; seeks light; seeks or avoids heat
- No brain or nervous system

2/9/16

18

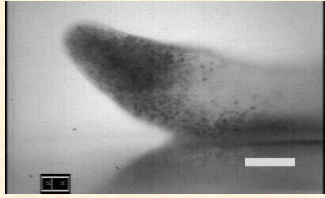
### Movement of Young Slug



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

2/9/16 (video < Zool.Inst.,Univ.München) 19

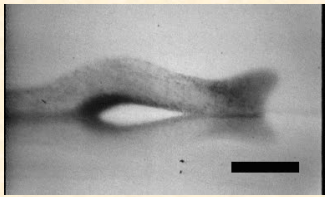
### Movement of Older Slug



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

2/9/16 (video < Zool.Inst.,Univ.München) 20


### Migration of Older Slug



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

2/9/16 (video < Zool.Inst.,Univ.München) 21

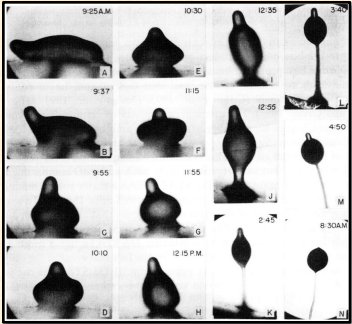
### Culmination Stage



- 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

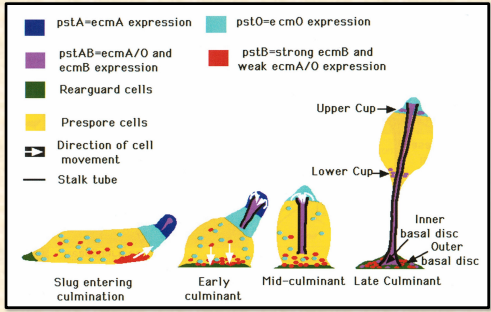
2/9/16 22

### Stages of Culmination



2/9/16 23

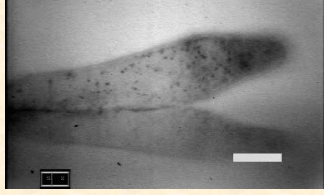
### Cell Differentiation at Culmination



2/9/16 (figure from Kessin, *Dictyostelium*) 24



### Early Culmination



- During early culmination all cell in prestalk rotate
- Scale bar = 50  $\mu\text{m}$ , 1 frame = 25 sec.

2/9/16

(video < Zool.Inst., Univ. München)

25

### Late Culmination



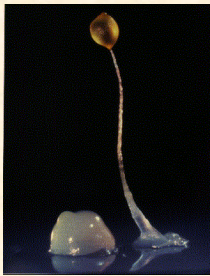
- Vigorous rotation at prestalk/pre-spore boundary
- Scale bar = 100  $\mu\text{m}$ , 1 frame = 10 sec.

2/9/16

(video < Zool.Inst., Univ. München)

26

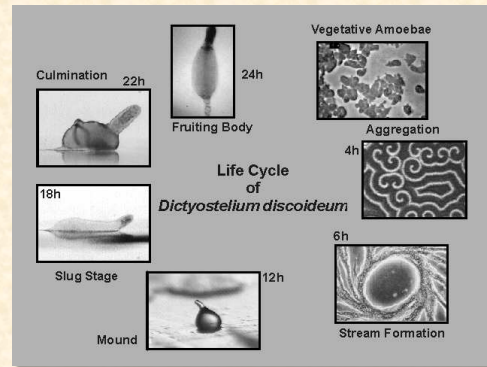
### Fruiting Body Stage



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

2/9/16

27



2/9/16

28

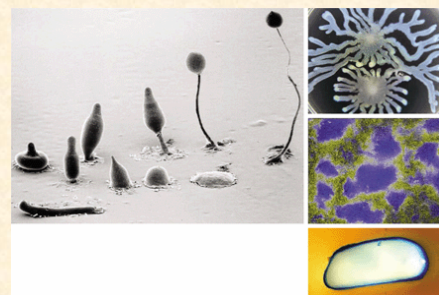
### Cooperation and Altruism in Dicty

- 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?

2/9/16

29

### Microbial Cooperation and Altruism

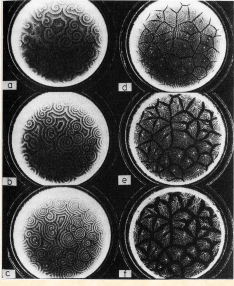


2/9/16  
Published by AAAS

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



### 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)

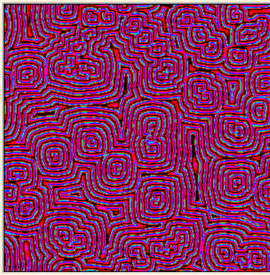
2/9/16 fig. from Solé & Goodwin 31

### Belousov-Zhabotinski Reaction



2/9/16 32

### Hodgepodge Machine



2/9/16 33

### Demonstration of Hodgepodge Machine

[Run NetLogo B-Z Reaction Simulator](#)  
 or  
[Run Hodgepodge simulator at CBN Online Experimentation Center](#)  
<mitpress.mit.edu/books/FLA0H/cbnhtml/java.html>

2/9/16 34

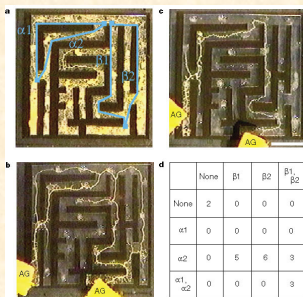
### Universal Properties

- 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*

2D

2/9/16 35

### Slime Mold Solving Maze



- Different slime mold: *Physarum polycephalum*
- Lengths:  $\alpha 1$  (41mm),  $\alpha 2$  (33),  $\beta 1$  (44),  $\beta 2$  (45)
- AG = food sources
- (a) initial, (b) exploring possible connections (4 hrs), (c) shortest (4 more)

	None	$\beta 1$	$\beta 2$	$\beta 1, \beta 2$
None	2	0	0	0
$\alpha 1$	0	0	0	0
$\alpha 2$	0	5	6	3
$\alpha 1, \alpha 2$	0	0	0	3

[fig. <Nakagaki, Yamada & Tóth, *Nature* 407, 470 (28 September 2000)]

2/9/16 36

### Slime Mold- Controlled Robot

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

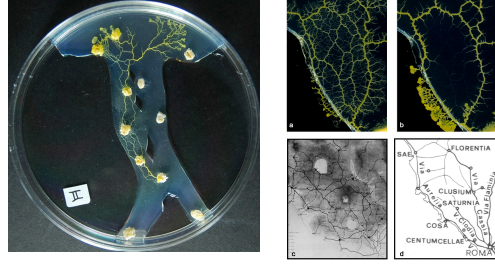


29/16

(Klaus-Peter Zauner, University of Southampton, UK, 2006)

37

### Slime Mold Computation of Roman Road Network



29/16

Strano, Adamatzky & Jones, *Int. J. Nanotech. & Mol. Comp.*, in press 38