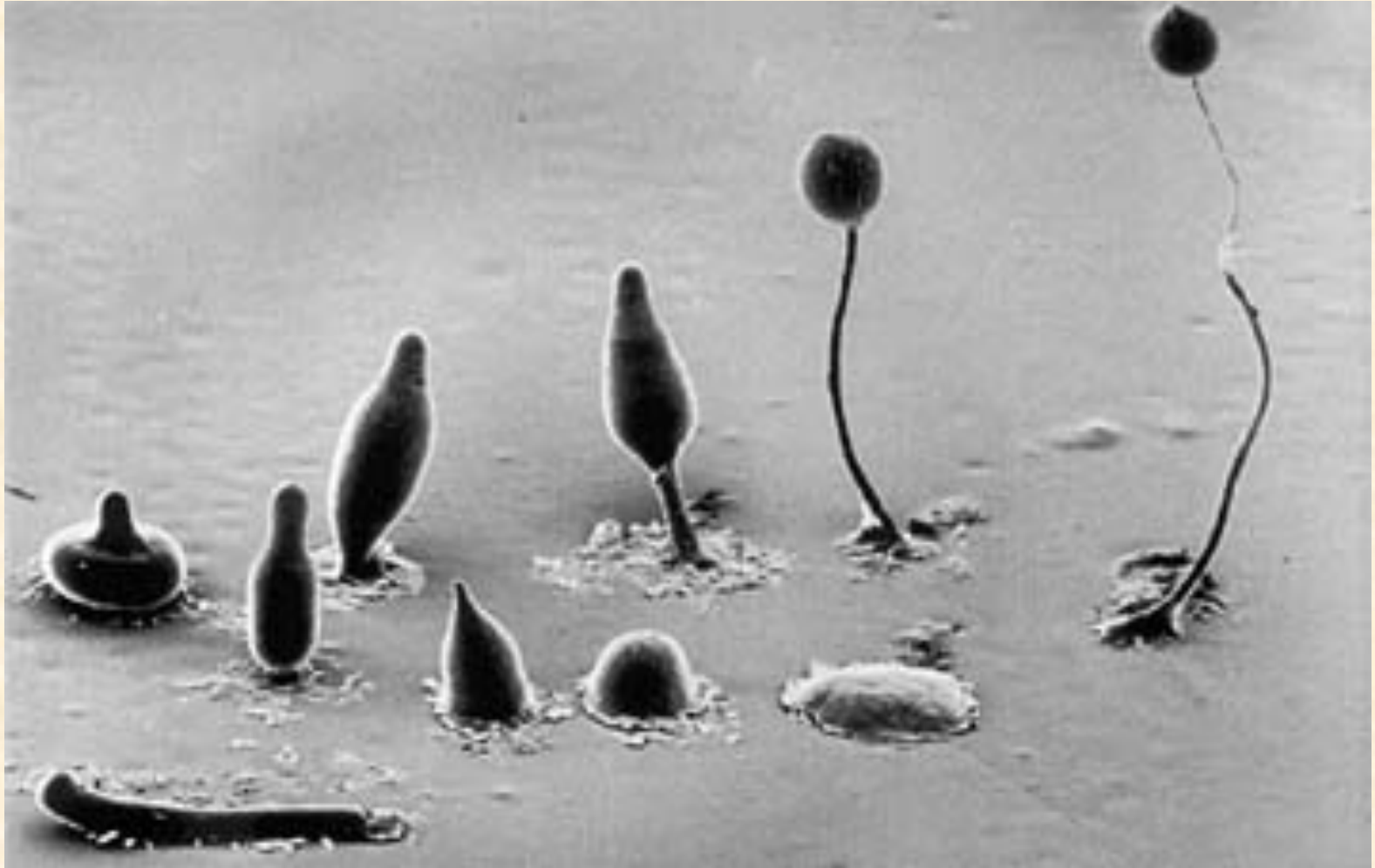


C.  
Slime Mold

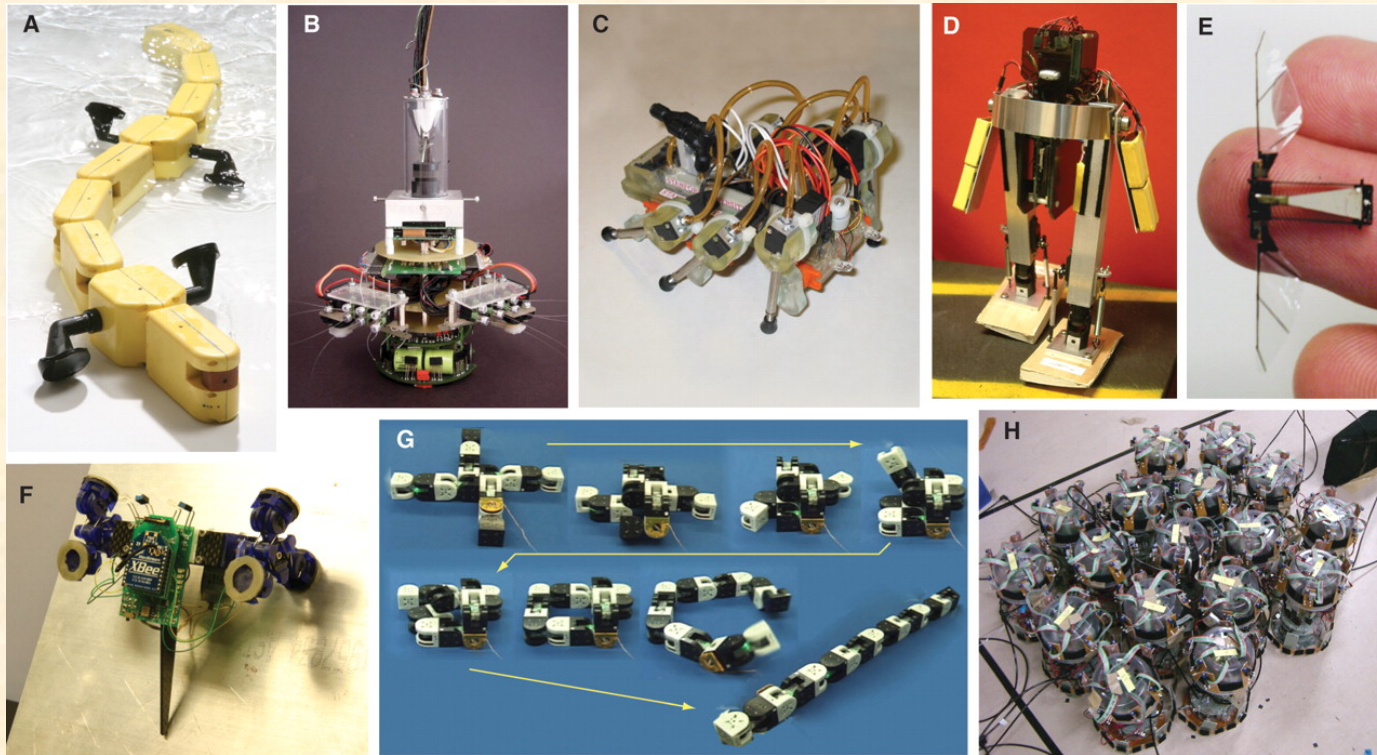
*(Dictyostelium discoideum)*

“Dicty”

# Complete Life Cycle



# Self-organization in Bio-inspired Robotics



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

# Self-copying Robot (2005)



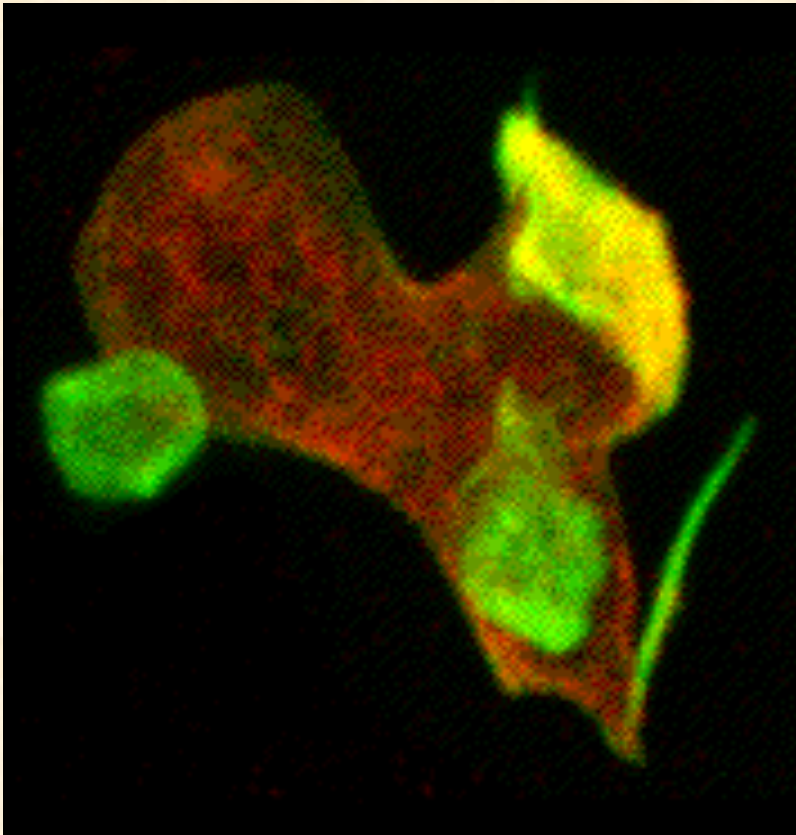
- Hod Lipson, Cornell
- Programmable blocks
- 2 swiveling pyramidal halves
- Magnetic connections
- 10 cm across
- One stack can assemble another



# Dicty Videos

- Bonner's videos
- Aggregation
- Life cycle

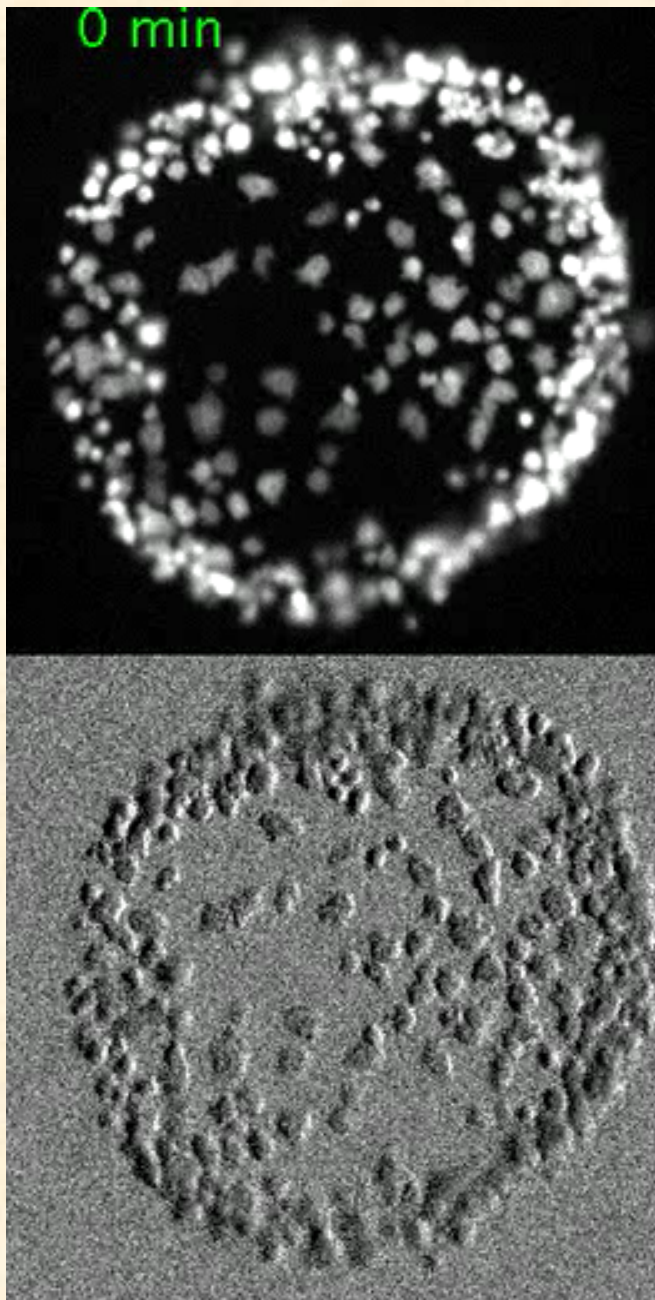
# Amoeba Stage



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

# Amoebas





# Aggregation Stage

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

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

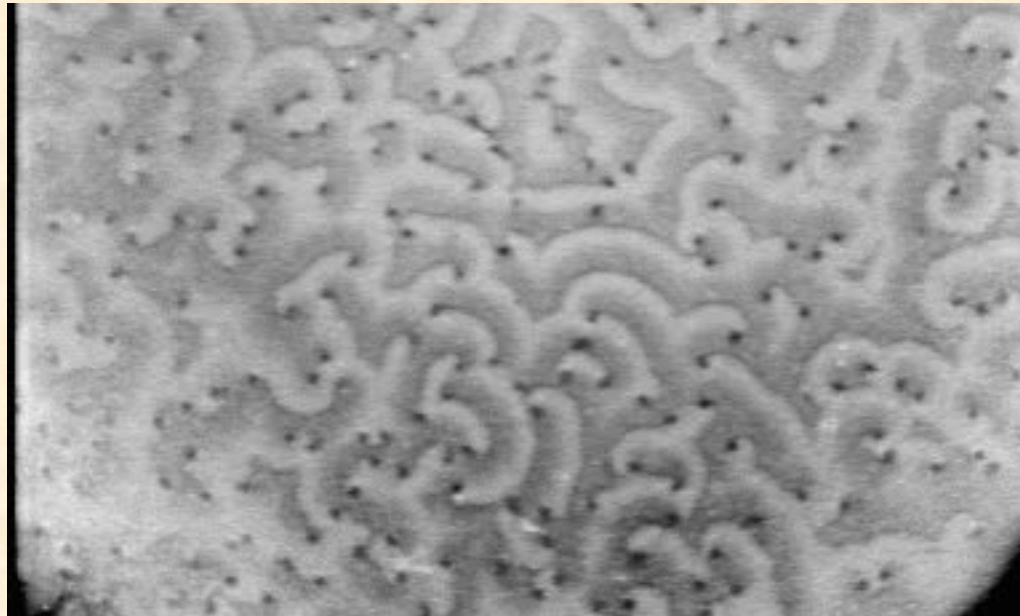


# Aggregation Stage



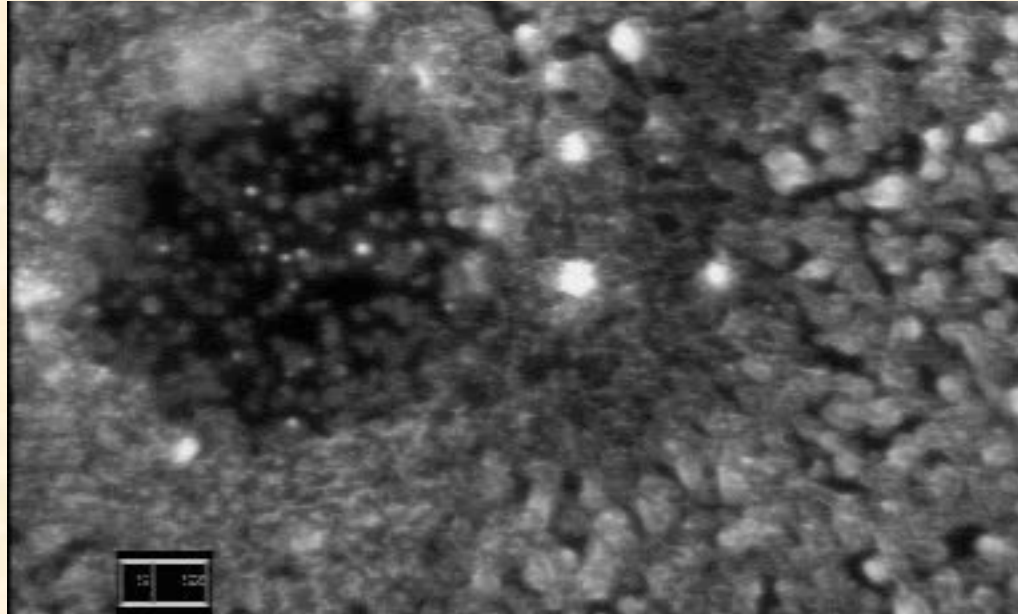
- Triggered by exhaustion of food
- Aggregate by *chemotaxis*
- Form expanding concentric rings and spirals
- Up to 125 000 individuals

# Spiral Waves



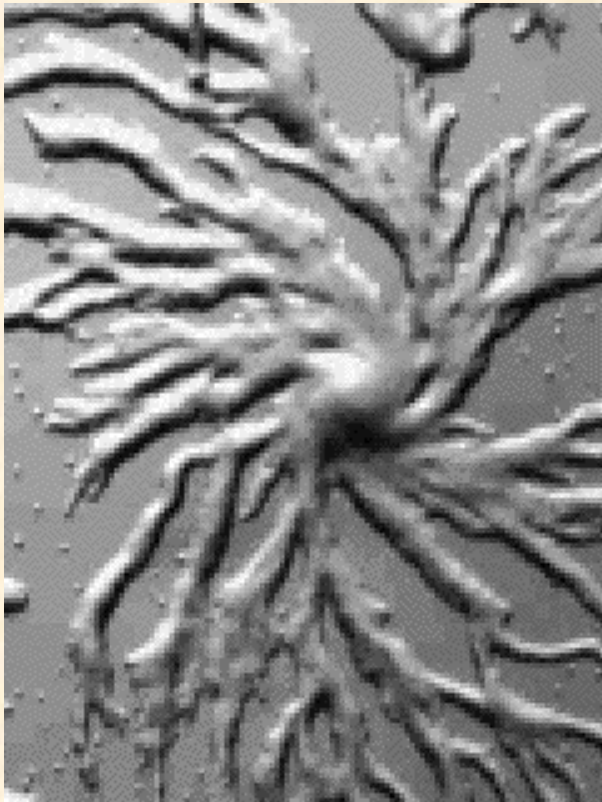
- Spiral accelerate cell aggregation (18 vs. 3  $\mu\text{m}/\text{min}.$ )
- Waves propagate 120 – 60  $\mu\text{m}/\text{min}.$
- 1 frame = 36 sec.

# Center of Spiral



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

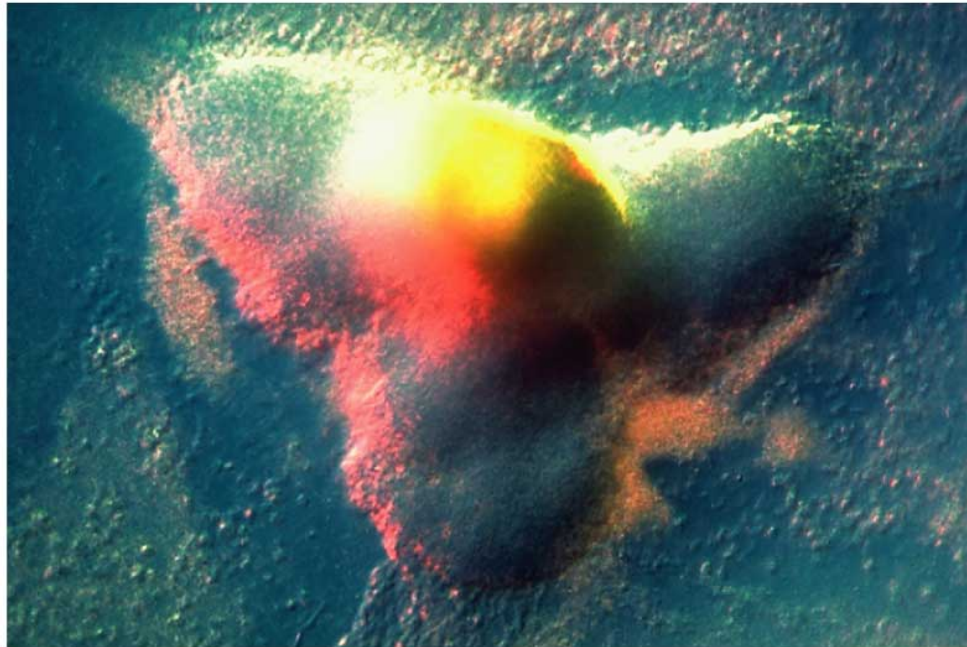
# Stream Formation Stage



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

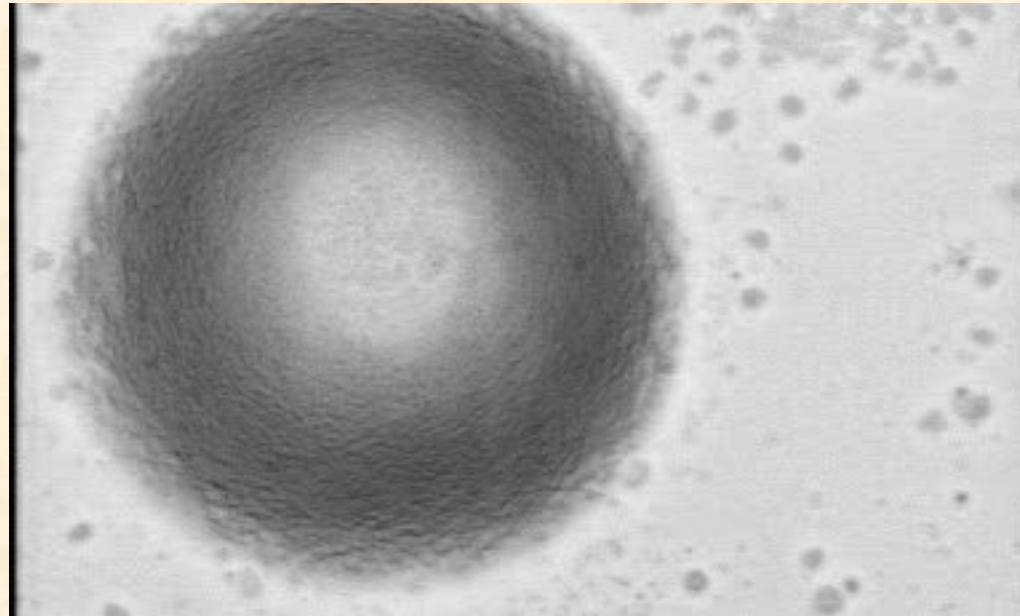


# Mound Stage



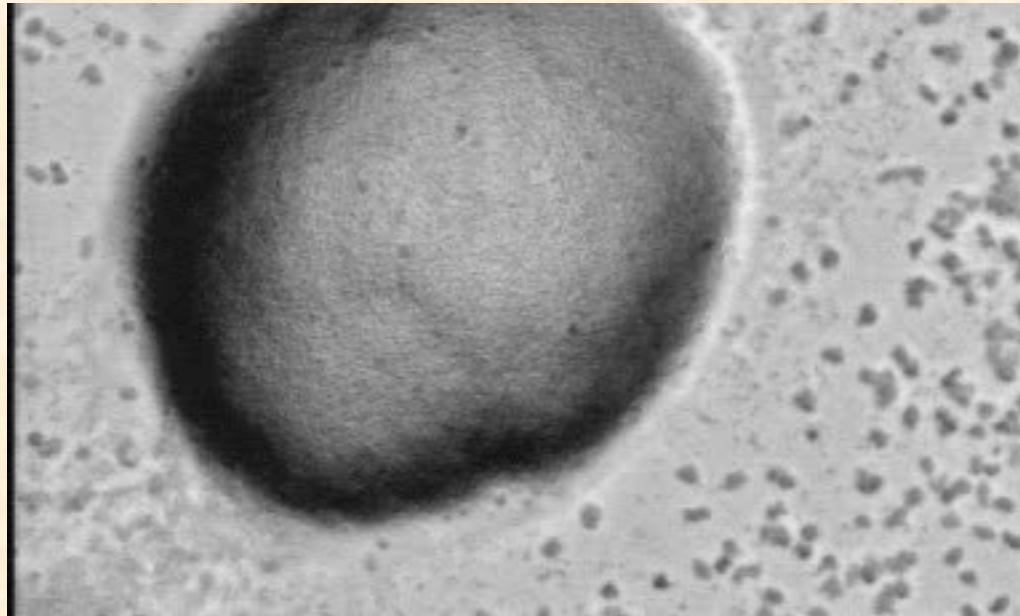
- Cells differentiate
- Some form an elongated finger

# Concentric Waves in Mounds



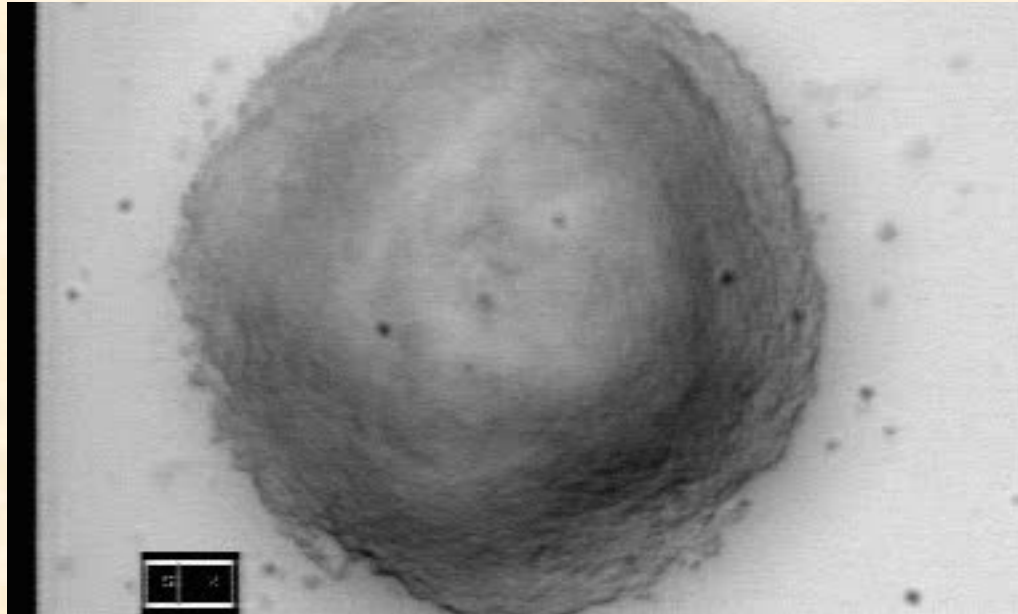
- Concentric or spiral waves
- Mound comprises  $10^3$  to  $10^5$  cells
- Cells begin to differentiate
- 1 frame = 20 sec.

# Multiple Centers



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

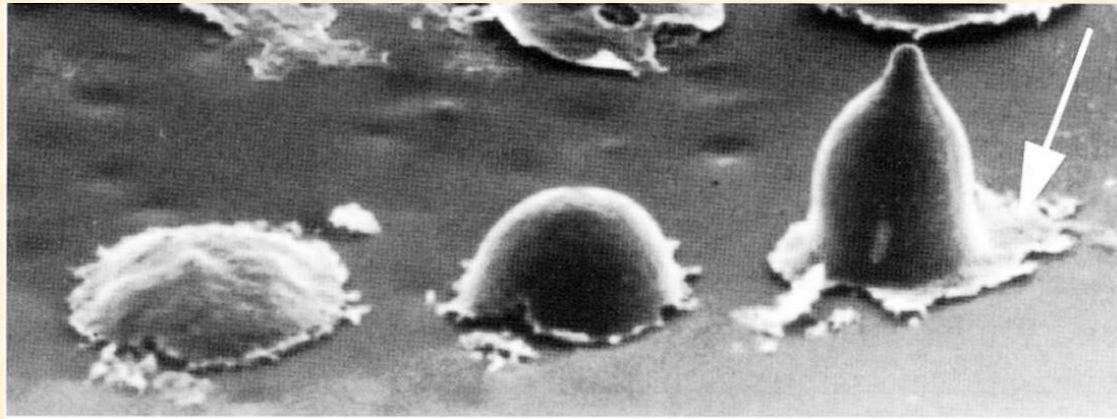
# Multi-armed Spirals



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



# Formation of Acellular Sheath



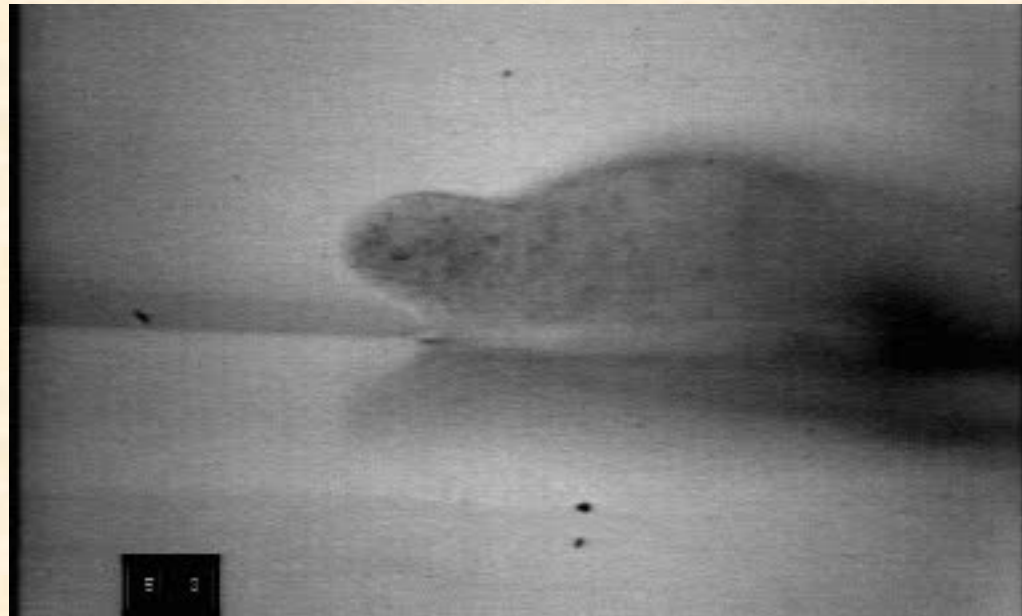
- Composed of cellulose & a large glycoprotein
- Covers mound and is left behind slug as trail
- Function not entirely understood:
  - protection from nematodes (worms)
  - control of diffusion of signaling molecules

# Slug Stage



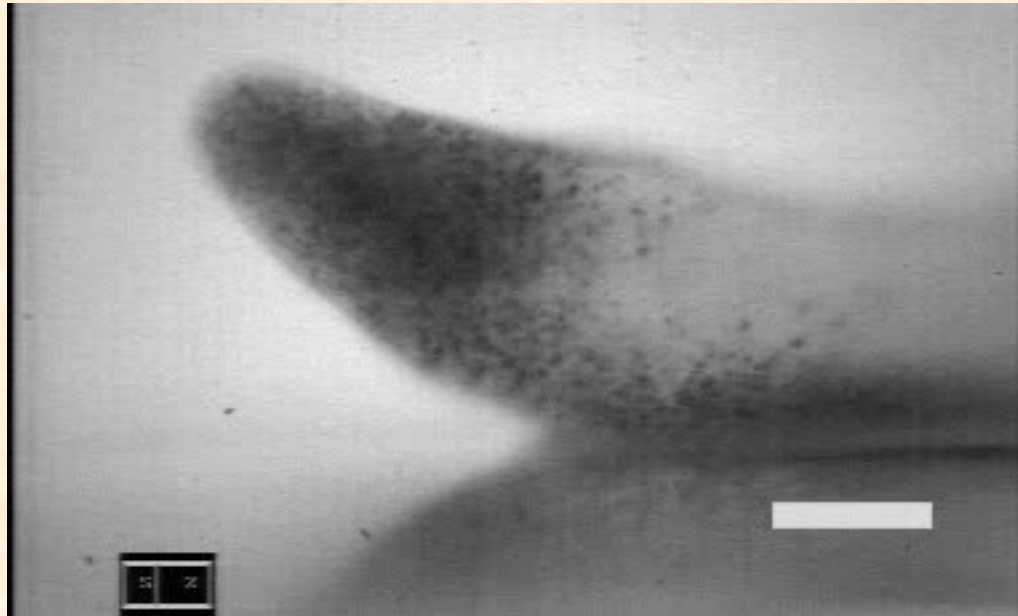
- Prestalk elongates, topples, to form slug
- Behaves as single organism with  $10^5$  cells
- Migrates; seeks light; seeks or avoids heat
- No brain or nervous system

# Movement of Young Slug



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

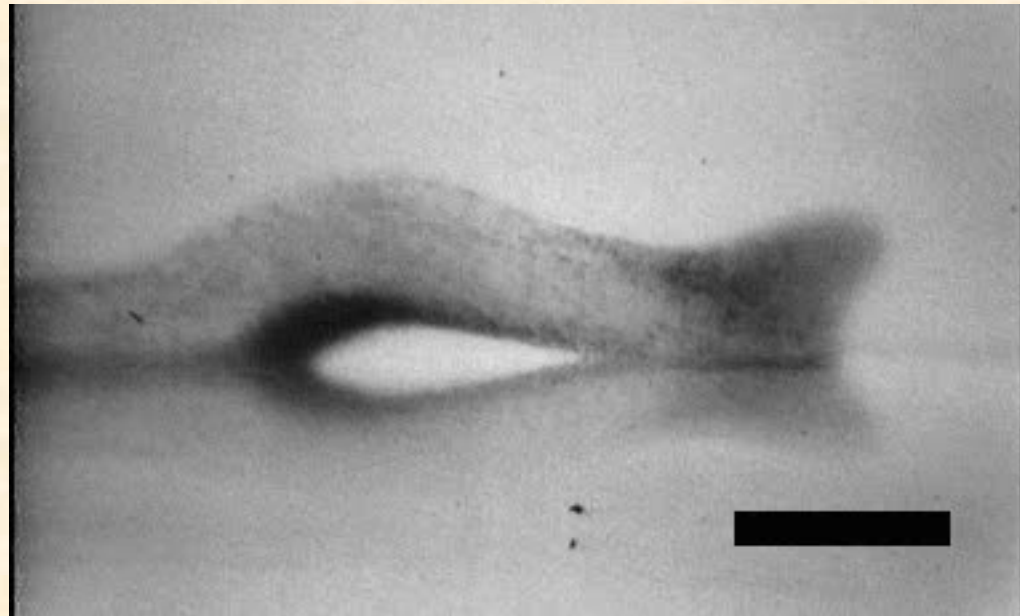
# Movement of Older Slug



- Note rotating prestalk cells in tip
- Pile of anterior-like cells on prestalk/prespore boundary
- Scale bar = 50  $\mu\text{m}$ , 1 frame = 5 sec.



# Migration of Older Slug



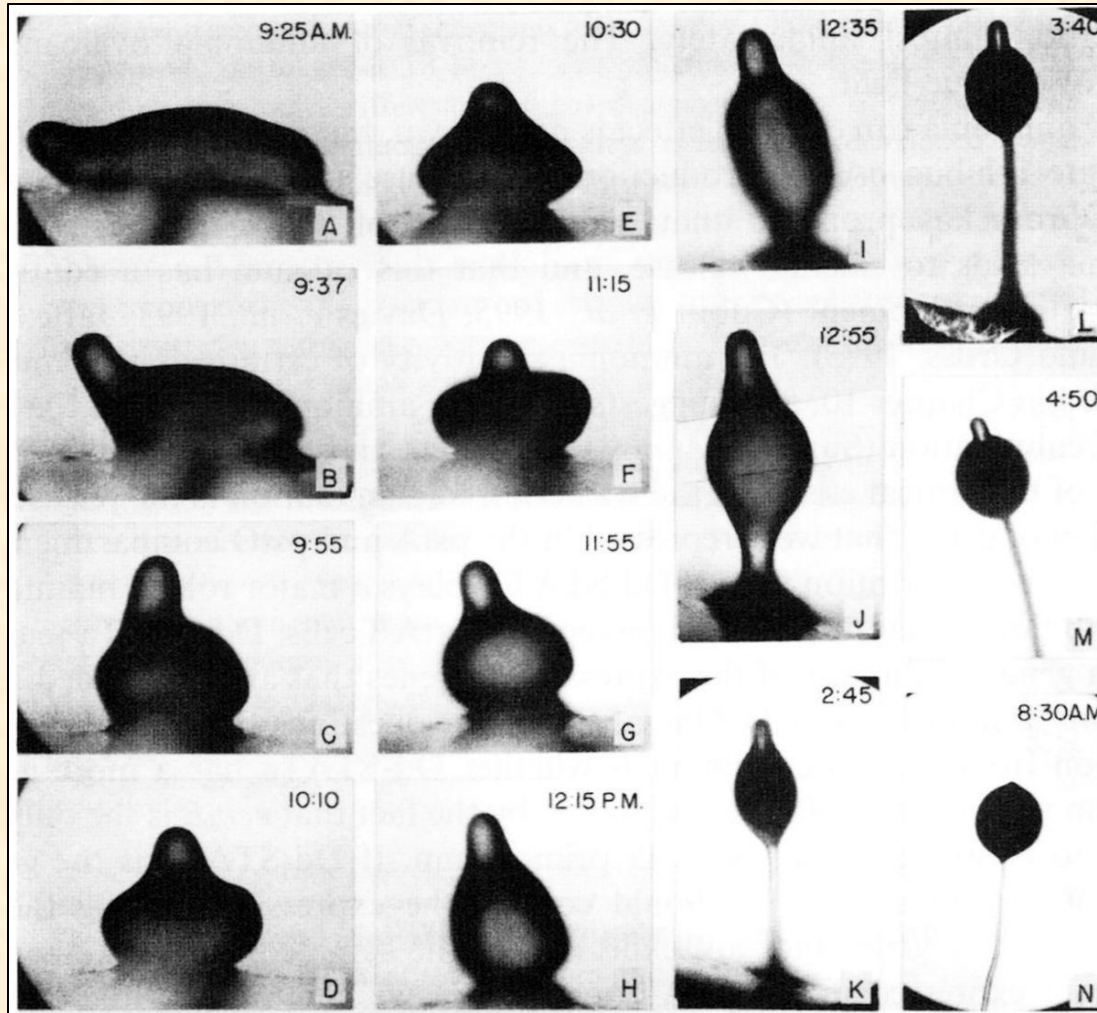
- Scale bar = 100  $\mu\text{m}$ , 1 frame = 20 sec.

# Culmination Stage

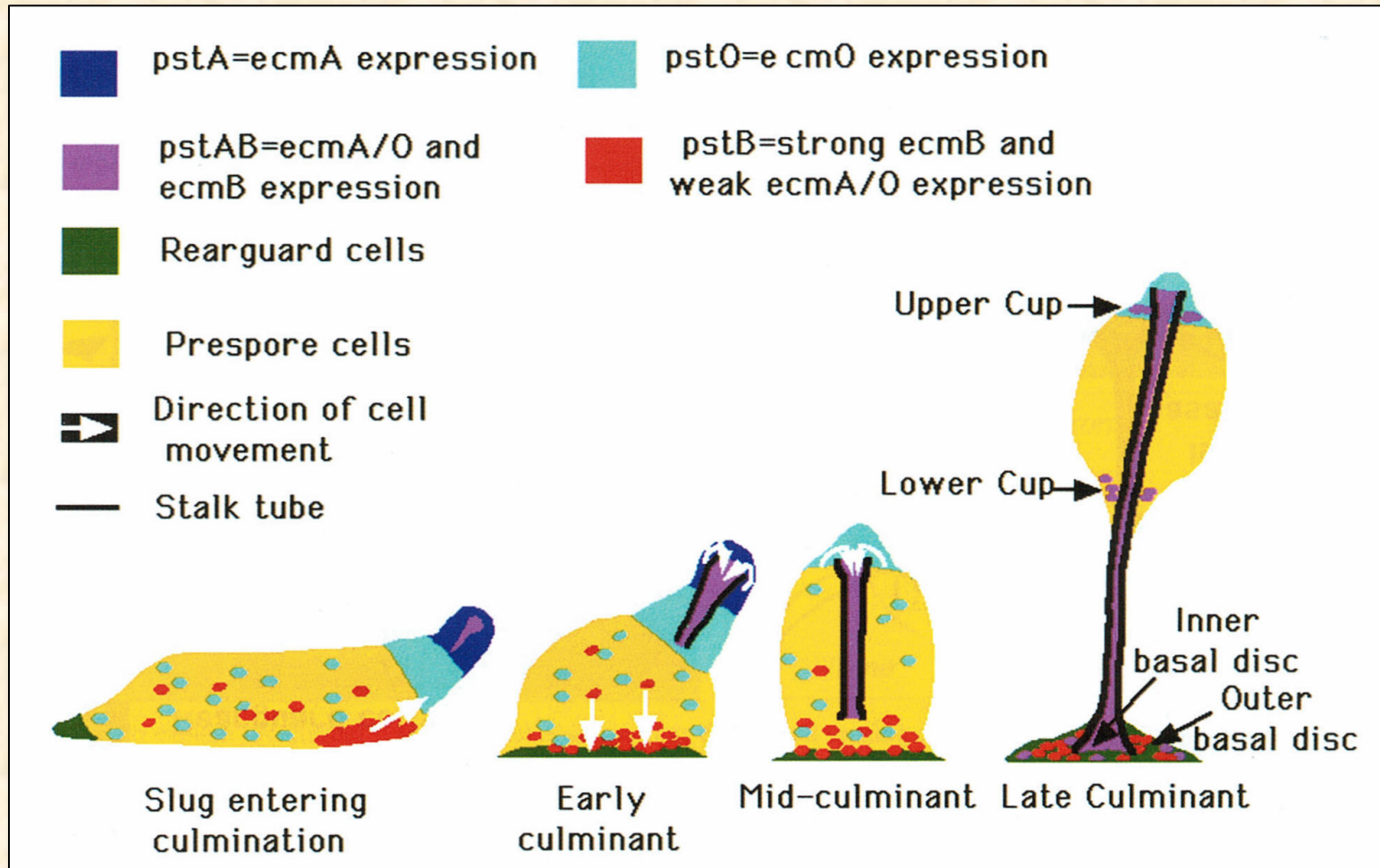


- Cells differentiate into base, stalk, and spores
- Prestalk cells form rigid bundles of cellulose & die
- Prespore cells (at end) cover selves with cellulose & become dormant

# Stages of Culmination

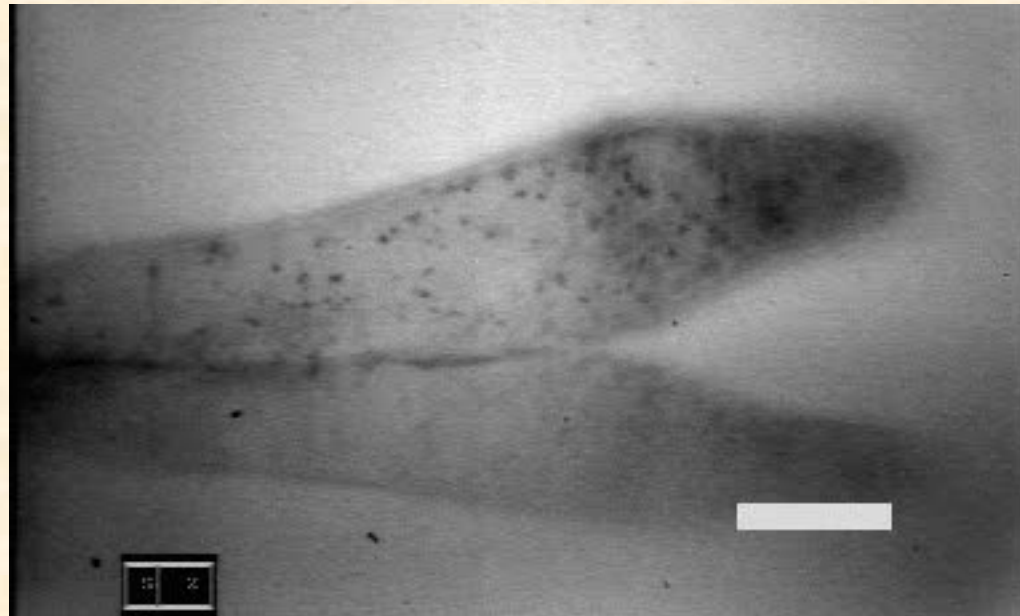


# Cell Differentiation at Culmination



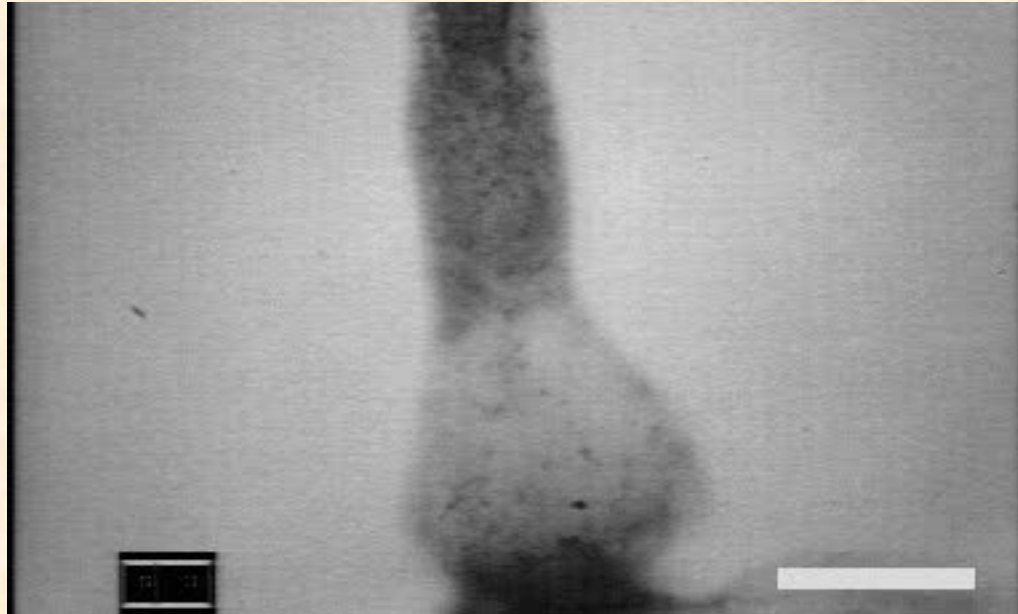


# Early Culmination



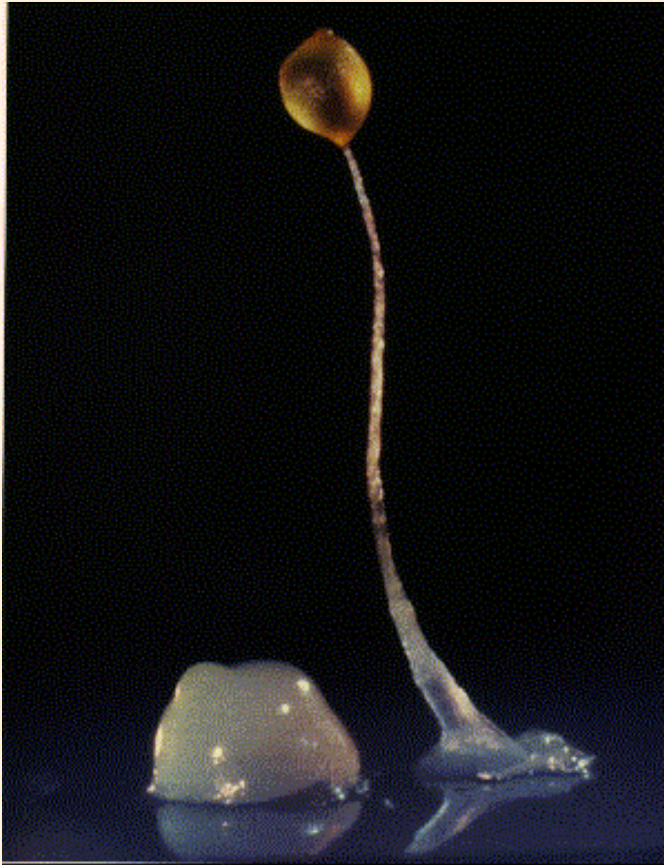
- During early culmination all cell in prestalk rotate
- Scale bar = 50  $\mu\text{m}$ , 1 frame = 25 sec.

# Late Culmination



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

# Fruiting Body Stage



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

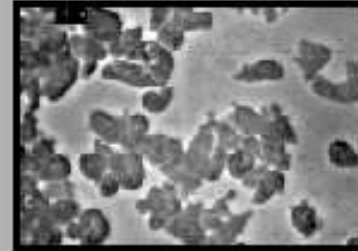
Culmination 22h



24h

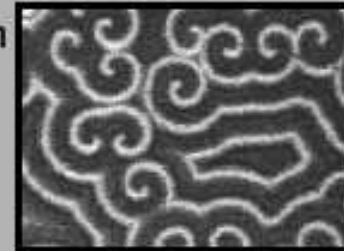
Fruiting Body

Vegetative Amoebae



Aggregation

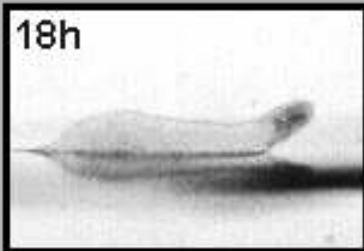
4h



Life Cycle  
of

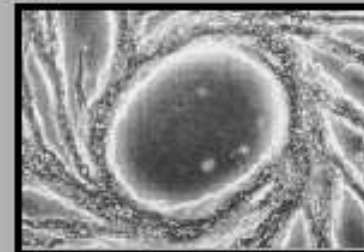
*Dictyostelium discoideum*

18h



Slug Stage

6h



Stream Formation

Mound



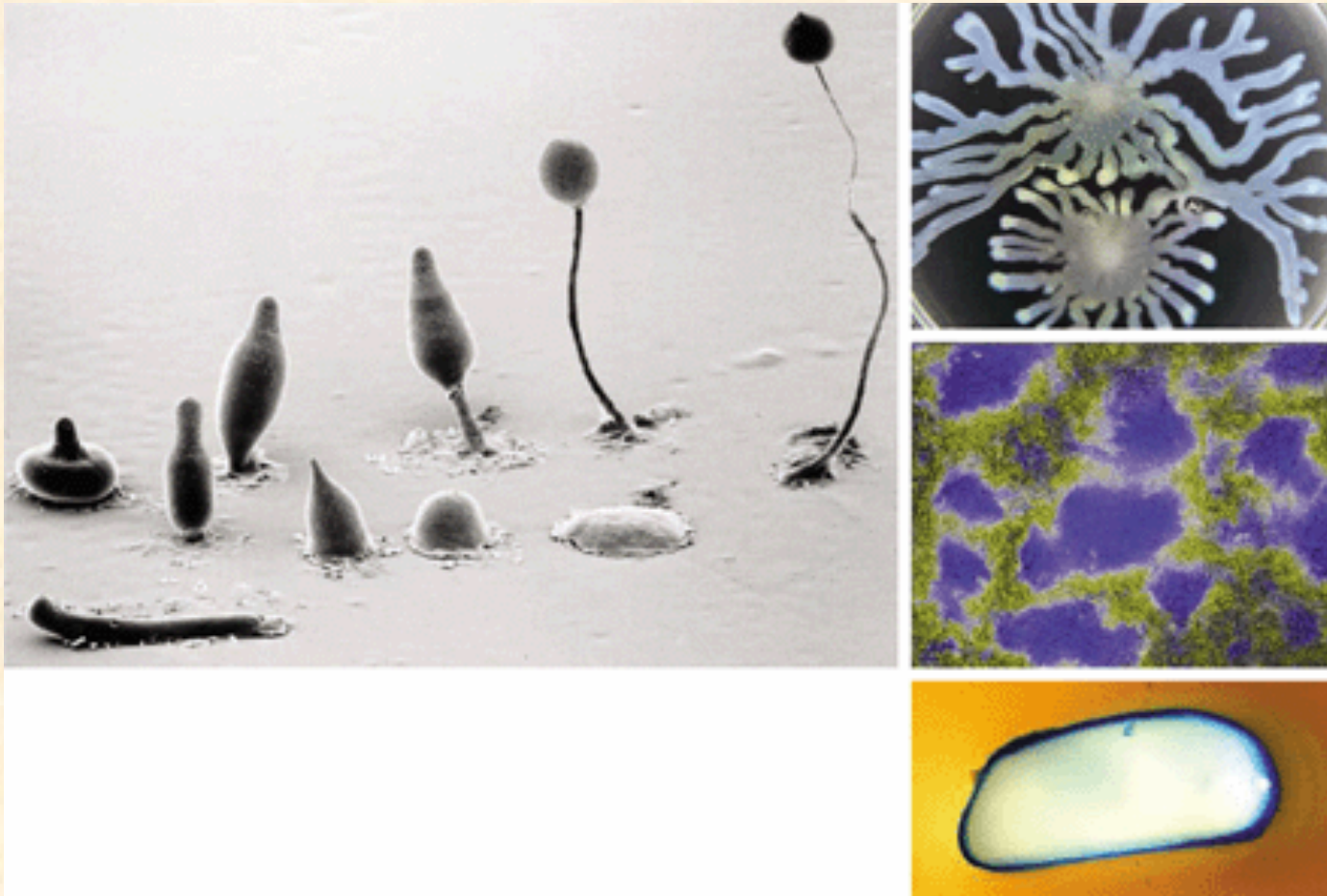
12h

# Cooperation and Altruism in Dicty

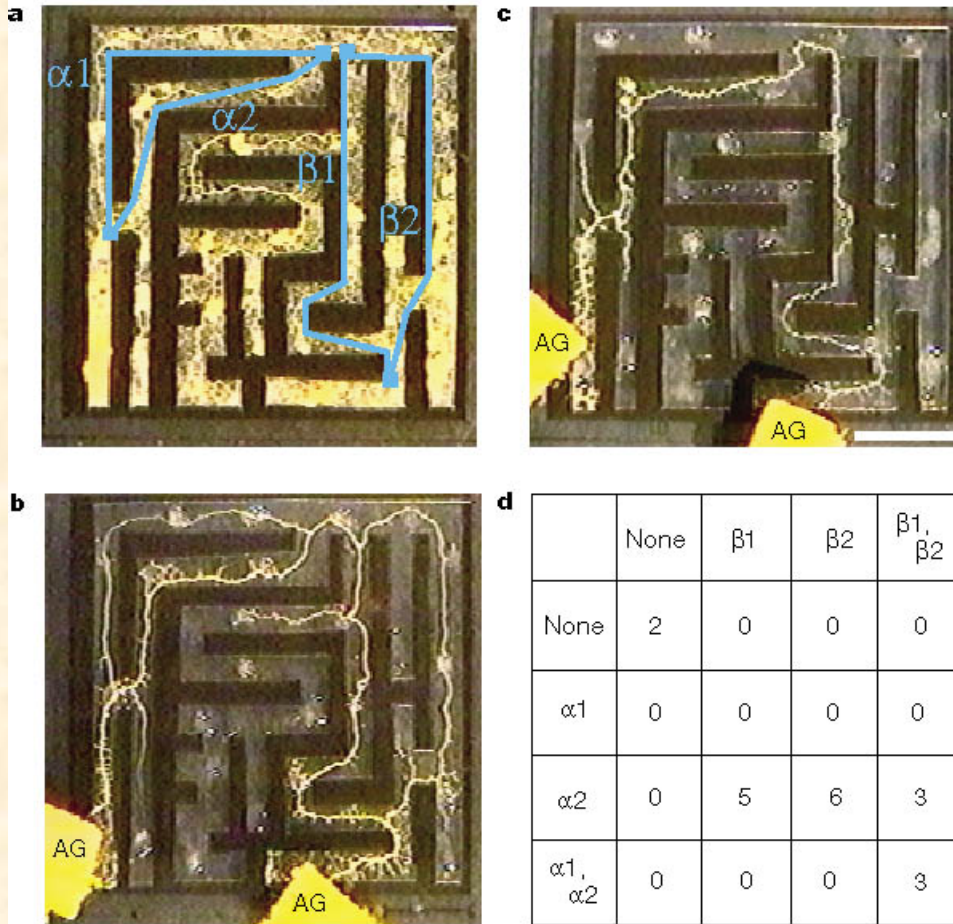
- Cooperation is essential to Dicty signaling and aggregation
- “Altruism” is essential in stalk formation
- How is cooperation encouraged and cheating discouraged?
- In one case the same gene prevents cheating and allows cohesion
- Green-beard genes?



# Microbial Cooperation and Altruism



# Slime Mold Solving Maze



- Different slime mold: *Physarum polycephalum*
- Lengths:  $\alpha 1$  (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)

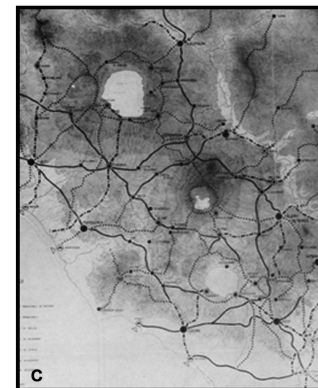
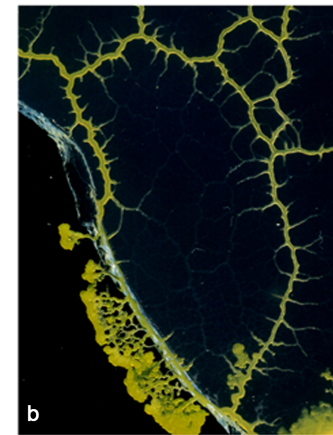
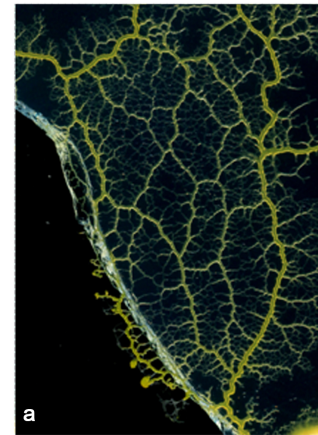
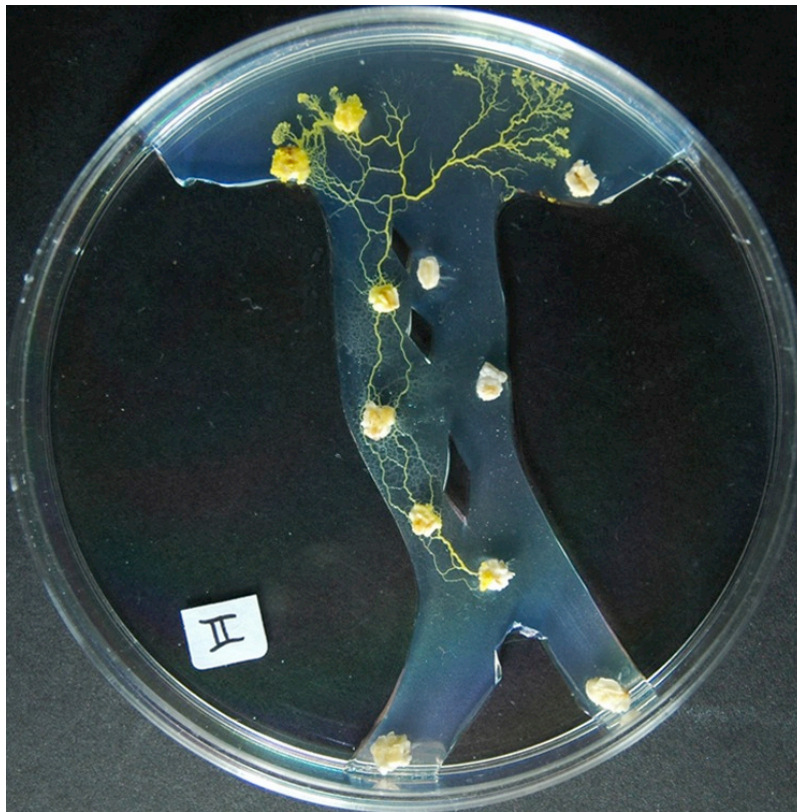
# Slime Mold- Controlled Robot

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

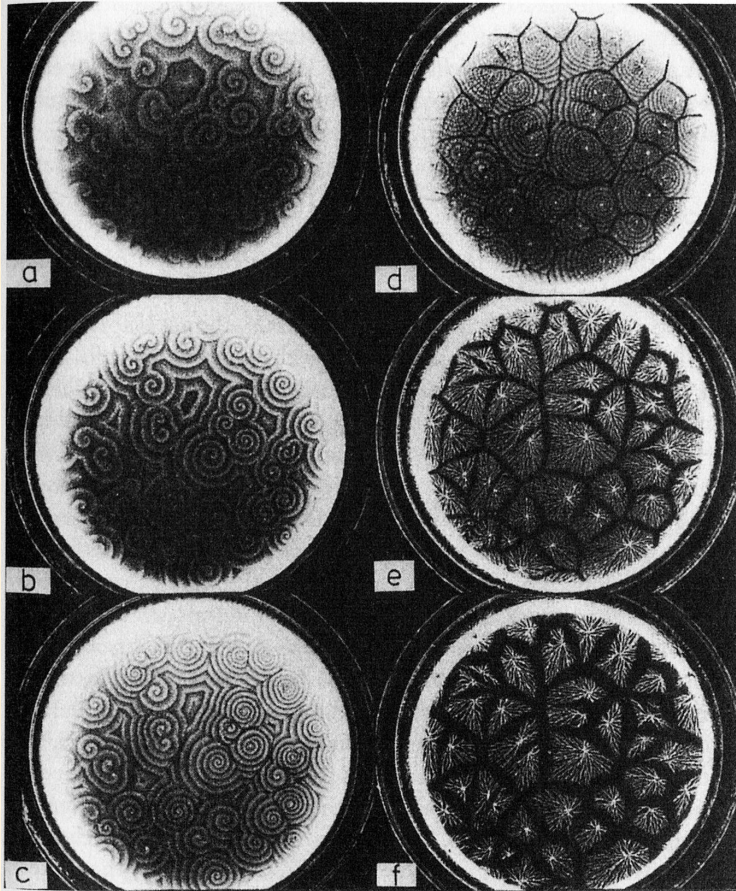




# Slime Mold Computation of Roman Road Network



# Emergent Patterns During Aggregation



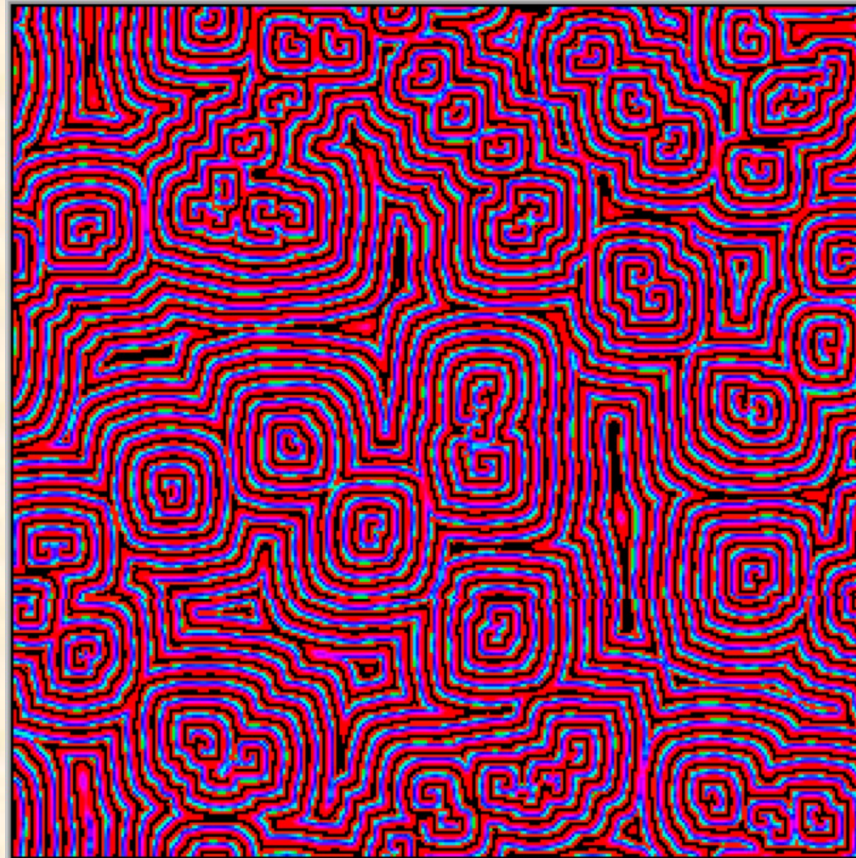
- a-c. As aggregate, wave lengths shorten
- d. Population divides into disjoint domains
- e-f. Domains contract into “fingers” (streaming stage)



# Belousov-Zhabotinski Reaction



# Hodgepodge Machine



# Demonstration of Hodgepodge Machine

Run NetLogo B-Z Reaction Simulator

or

Run Hodgepodge simulator at CBN  
Online Experimentation Center

[mitpress.mit.edu/books/FLAOH/cbnhtml/java.html](http://mitpress.mit.edu/books/FLAOH/cbnhtml/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

