

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)

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Published by AAAS

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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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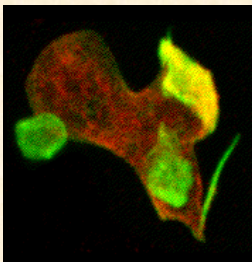
Dicty Videos

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

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Amoeba Stage




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

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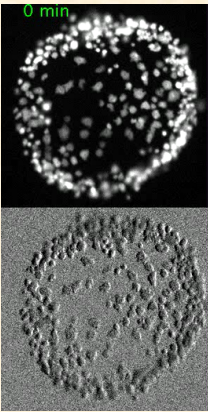
Amoebas



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A light micrograph showing several amoebas. Some are individual, while others are in small clusters. They have a distinct shape with a central vacuole and a nucleus.

Aggregation Stage




0 min

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

29/16 Science 21 May 2010: Vol. 328, 1021-1025
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Two micrographs showing the aggregation stage of a slime mold. The top image shows a circular aggregate of cells at 0 minutes. The bottom image shows a similar aggregate at a later time, with cells beginning to form concentric rings.

Aggregation Stage

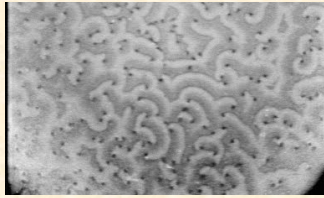


- Triggered by exhaustion of food
- Aggregate by *chemotaxis*
- Form expanding concentric rings and spirals
- Up to 125 000 individuals

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A micrograph showing the aggregation stage of a slime mold, with cells forming concentric rings and spirals.

Spiral Waves



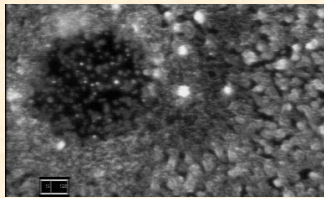
- Spiral accelerate cell aggregation (18 vs. 3 $\mu\text{m}/\text{min}$.)
- Waves propagate 120–60 $\mu\text{m}/\text{min}$.
- 1 frame = 36 sec.

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(video < Zool.Inst.,Univ.München)

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Center of Spiral



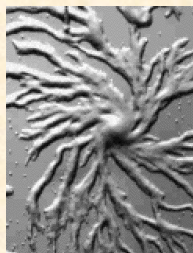
- Mechanisms of spiral formation are still unclear
- Involves symmetry breaking
- 1 frame = 10 sec.

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(video < Zool.Inst.,Univ.München)

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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*

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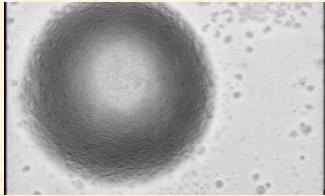
Mound Stage



- Cells differentiate
- Some form an elongated finger

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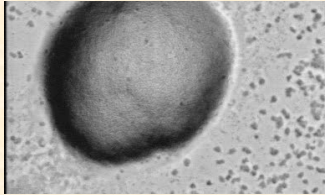
Concentric Waves in Mounds



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

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(video < Zool.Inst.,Univ.München)

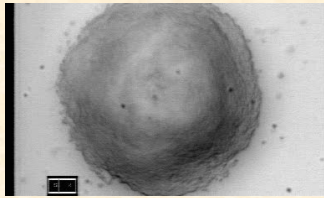
Multiple Centers



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

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(video < Zool.Inst.,Univ.München)

Multi-armed Spirals



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

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(video < Zool.Inst.,Univ.München)

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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

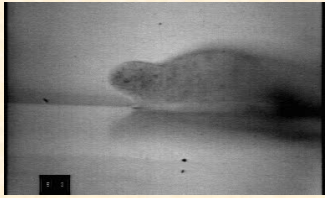


- Prestalk elongates, topples, to form slug
- Behaves as single organism with 10^5 cells
- Migrates; seeks light; seeks or avoids heat
- No brain or nervous system

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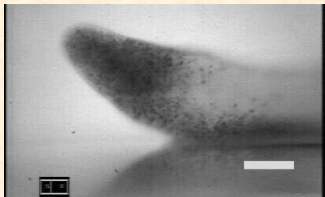
Movement of Young Slug



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

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

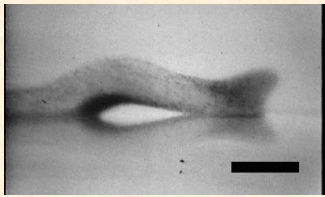
Movement of Older Slug



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

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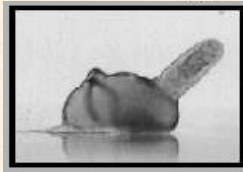
Migration of Older Slug



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

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Culmination Stage

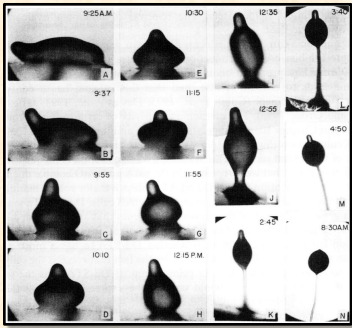


- Cells differentiate into base, stalk, and spores
- Prestalk cells form rigid bundles of cellulose & die
- Prespore cells (at end) cover selves with cellulose & become dormant

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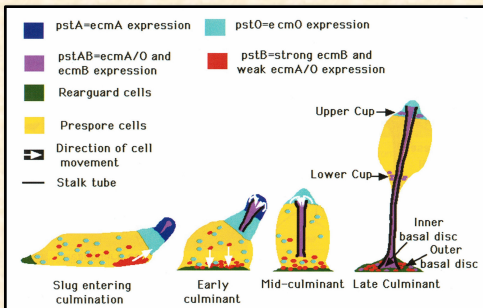
Stages of Culmination



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Cell Differentiation at Culmination

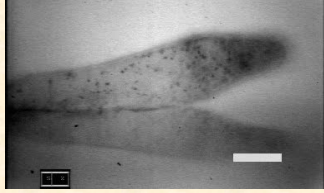


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(figure from Kessin, *Dictyostelium*)

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Early Culmination



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

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(video < Zool.Inst.,Univ.München)

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Late Culmination



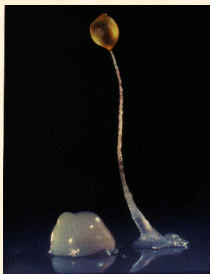
- Vigorous rotation at prestalk/pre-spore boundary
- Scale bar = 100 μm , 1 frame = 10 sec.

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(video < Zool.Inst.,Univ.München)

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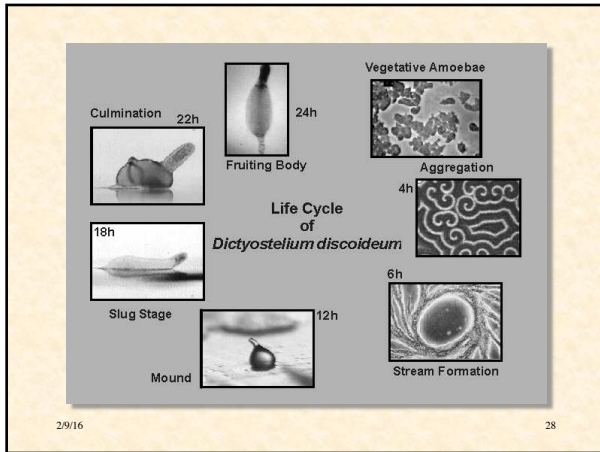
Fruiting Body Stage



- 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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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?

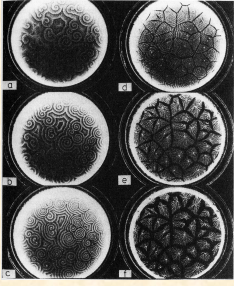
Microbial Cooperation and Altruism

The image shows various stages of microbial cooperation and altruism. On the left, a series of images shows the development of a multicellular organism from individual cells. On the right, there are three smaller images: a blue branching structure, a purple and green cellular structure, and a single blue cell.

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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)

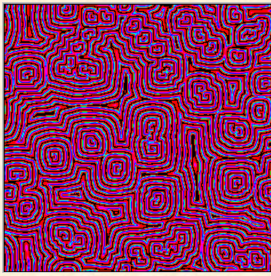
2/9/16 fig. from Solé & Goodwin 31

Belousov-Zhabotinski Reaction



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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](#)

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

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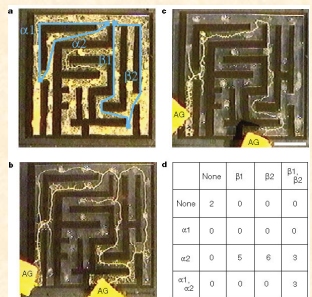
Universal Properties

- 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*

 2D

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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	0
$\alpha 1$	0	0	0	0	0
$\alpha 2$	0	5	6	3	
$\alpha 1$, $\alpha 2$	0	0	0	3	

2/9/16 [fig. <Nakagaki, Yamada & Toth, *Nature* 407, 470 (28 September 2000)] 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*

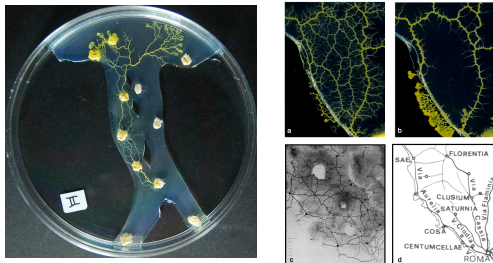


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(Klaus-Peter Zauner, University of Southampton, UK, 2006)

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Slime Mold Computation of Roman Road Network



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