Lecture 10

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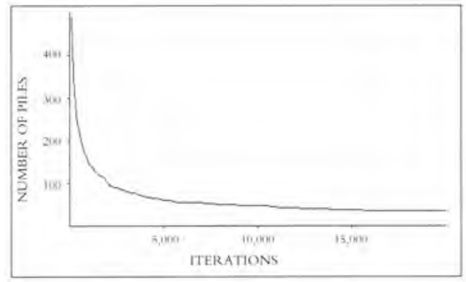
Decrease in Number of Piles



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Why does the number of piles decrease?

- A pile can grow or shrink
- But once the last chip is taken from a pile, it can never restart
- Is there any way the number of piles can increase?
- Yes, and existing pile can be broken into two

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More Termites

Termites	2000 steps		10 000 steps		
	num. piles	avg. size	num. piles	avg. size	chips in piles
1000	102	15	47	30	
4000	10		3	80	240

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Termite-Mediated Condensation

- Number of chips is conserved
- Chips do not move on own; movement is mediated by termites
- Chips preferentially condense into piles
- Increasing termites, increases number of chips in fluid (randomly moving) state
- Like temperature

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An Experiment to Make the Number Decrease More Quickly

- Problem: piles may grow or shrink
- Idea: protect “investment” in large piles
- Termites will not take chips from piles greater than a certain size
- Result: number decreases more quickly
- Most chips are in piles
- But *never* got less than 82 piles

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Conclusion

- In the long run, the "dumber" strategy is better
- Although it's slower, it achieves a better result
- By not protecting large piles, there is a small probability of any pile evaporating
- So the smaller "large piles" can evaporate and contribute to the larger "large piles"
- Even though this strategy makes occasional backward steps, it outperforms the attempt to protect accomplishments

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Mound Building by *Macrotermes* Termites

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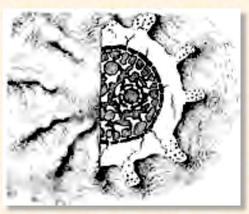
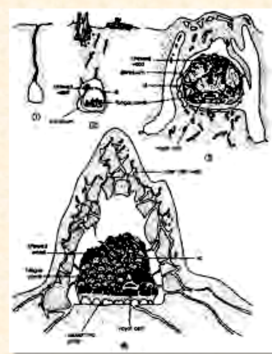
Structure of Mound



9/25/07 figs. from Lüscher (1961) 9

Construction of Mound



(1) First chamber made by royal couple

(2, 3) Intermediate stages of development

(4) Fully developed nest

9/25/07 Fig. from Wilson (1971) 10

Termite Nests

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Alternatives to Self-Organization

- Leader
  - directs building activity of group
- Blueprint (image of completion)
  - compact representation of spatial/temporal relationships of parts
- Recipe (program)
  - sequential instructions specify spatial/temporal actions of individual
- Template
  - full-sized guide or mold that specifies final pattern

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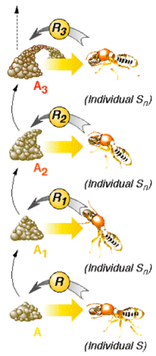
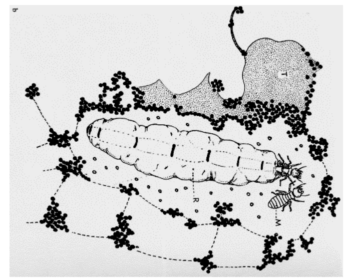


Basic Mechanism of Construction (Stigmergy)

- Worker picks up soil granule
- Mixes saliva to make cement
- Cement contains pheromone
- Other workers attracted by pheromone to bring more granules
- There are also trail and queen pheromones

9/25/07 Fig. from Solé & Goodwin 13

Construction of Royal Chamber



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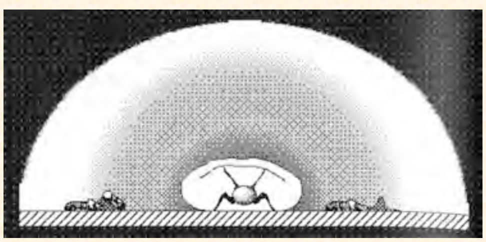
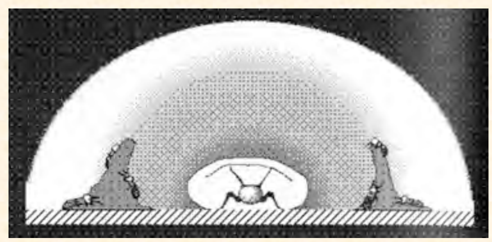
Construction of Arch (1)



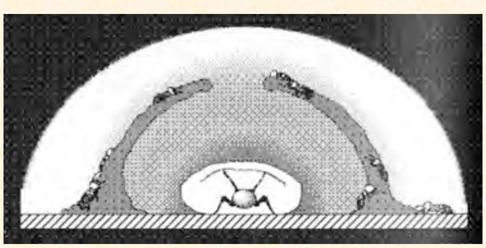
9/25/07 Fig. from Bonabeau, Dorigo & Theraulaz 15

Construction of Arch (2)



9/25/07 Fig. from Bonabeau, Dorigo & Theraulaz 16

Construction of Arch (3)



9/25/07 Fig. from Bonabeau, Dorigo & Theraulaz 17

Basic Principles

- Continuous (quantitative) stigmergy
- Positive feedback:
  - via pheromone deposition
- Negative feedback:
  - depletion of soil granules & competition between pillars
  - pheromone decay

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Deneubourg Model

- $H(r, t)$ = concentration of cement pheromone in air at location r & time t
- $P(r, t)$ = amount of deposited cement with still active pheromone at r, t
- $C(r, t)$ = density of laden termites at r, t
- Φ = constant flow of laden termites into system

Equation for P
(Deposited Cement with Pheromone)

$\partial_t P$ (rate of change of active cement) =
$k_1 C$ (rate of cement deposition by termites)
$- k_2 P$ (rate of pheromone loss to air)

$$\partial_t P = k_1 C - k_2 P$$

Equation for H
(Concentration of Pheromone)

$\partial_t H$ (rate of change of concentration) =
$k_2 P$ (pheromone from deposited material)
$- k_4 H$ (pheromone decay)
$+ D_H \nabla^2 H$ (pheromone diffusion)

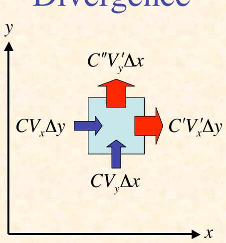
$$\partial_t H = k_2 P - k_4 H + D_H \nabla^2 H$$

Equation for C
(Density of Laden Termites)

$\partial_t C$ (rate of change of concentration) =
Φ (flux of laden termites)
$- k_1 C$ (unloading of termites)
$+ D_C \nabla^2 C$ (random walk)
$- \gamma \nabla \cdot (C \nabla H)$ (chemotaxis: response to pheromone gradient)

$$\partial_t C = \Phi - k_1 C + D_C \nabla^2 C - \gamma \nabla \cdot (C \nabla H)$$

Explanation of Divergence



- velocity field = $\mathbf{V}(x,y) = \mathbf{i} V_x(x,y) + \mathbf{j} V_y(x,y)$
- $C(x,y)$ = density
- outflow rate = $\Delta_x(CV_x)\,\Delta y + \Delta_y(CV_y)\,\Delta x$
- outflow rate / unit area

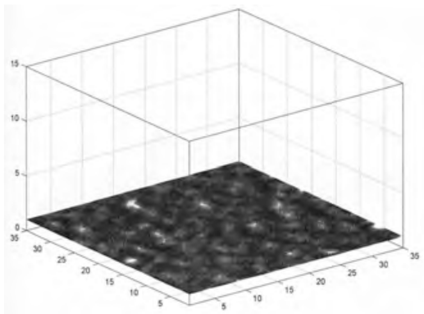
$$= \frac{\Delta_x(CV_x)}{\Delta x} + \frac{\Delta_y(CV_y)}{\Delta y}$$

$$\to \frac{\partial(CV_x)}{\partial x} + \frac{\partial(CV_y)}{\partial y} = \nabla \cdot C\mathbf{V}$$

Explanation of Chemotaxis Term

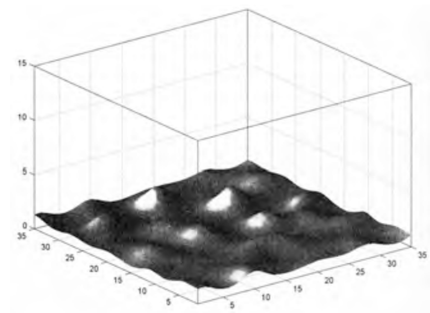
- The termite flow *into* a region is the *negative* divergence of the flux through it
  $-\nabla \cdot \mathbf{J} = -(\partial J_x / \partial x + \partial J_y / \partial y)$
- The flux velocity is proportional to the pheromone gradient
  $\mathbf{J} \propto \nabla H$
- The flux density is proportional to the number of moving termites
  $\mathbf{J} \propto C$
- Hence, $-\gamma \nabla \cdot \mathbf{J} = -\gamma \nabla \cdot (C \nabla H)$

Simulation ($T = 0$)



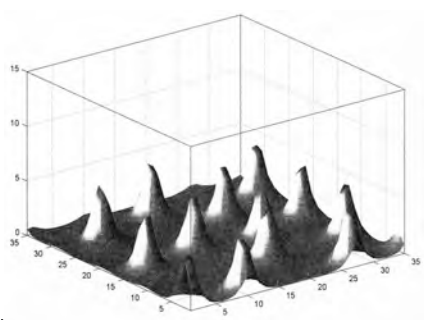
9/25/07 fig. from Solé & Goodwin 25

Simulation ($T = 100$)



9/25/07 fig. from Solé & Goodwin 26

Simulation ($T = 1000$)



9/25/07 fig. from Solé & Goodwin 27

Conditions for Self-Organized Pillars

- Will not produce regularly spaced pillars if:
  - density of termites is too low
  - rate of deposition is too low
- A homogeneous stable state results

$$C_0 = \frac{\Phi}{k_1}, \qquad H_0 = \frac{\Phi}{k_4}, \qquad P_0 = \frac{\Phi}{k_2}$$

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Interaction of Three Pheromones

- Queen pheromone governs size and shape of queen chamber (template)
- Cement pheromone governs construction and spacing of pillars & arches (stigmergy)
- Trail pheromone:
  - attracts workers to construction sites (stigmergy)
  - encourages soil pickup (stigmergy)
  - governs sizes of galleries (template)

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