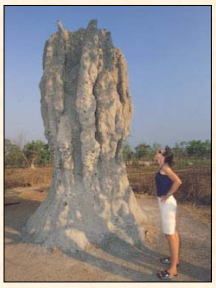
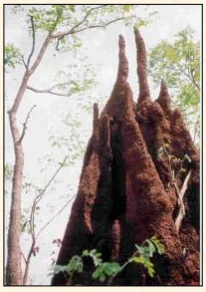
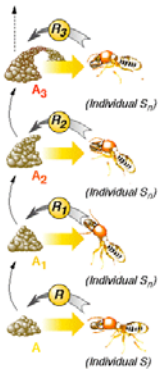
Termite Nests





Alternatives to Self-Organization

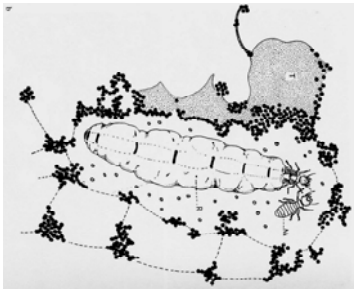
- Leader
  - directs building activity of group
- Blueprint (image of completion)
  - compact representation of spatial/temporal relationships of parts
- Recipe (program)
  - sequential instructions specify spatial/temporal actions of individual
- Template
  - full-sized guide or mold that specifies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



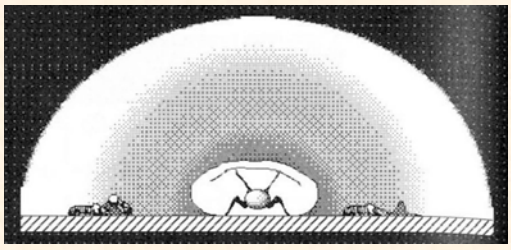
Basic Mechanism of Construction (Stigmergy)

- 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

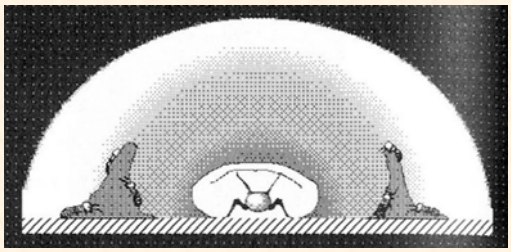
Construction of Royal Chamber



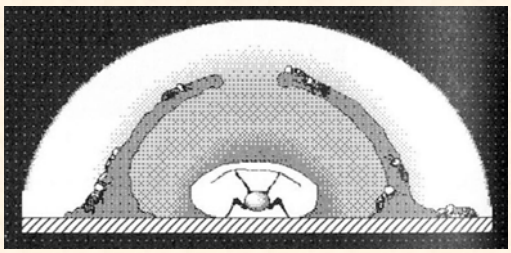
Construction of Arch (1)



Construction of Arch (2)



Construction of Arch (3)



Basic Principles

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

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)

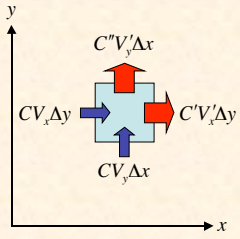
$$\partial_t H = k_2 P - k_4 H + D_H \nabla^2 H$$

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)

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

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

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

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

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 ($T = 0$)

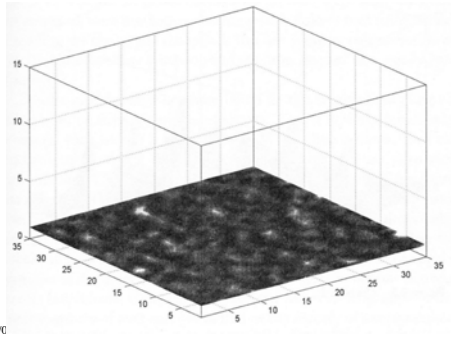


fig. from Solé & Goodwin

Simulation ($T = 100$)

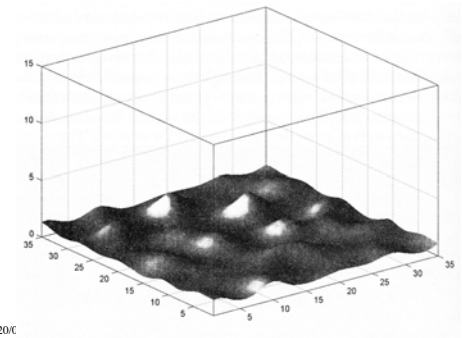


fig. from Solé & Goodwin

Simulation ($T = 1000$)

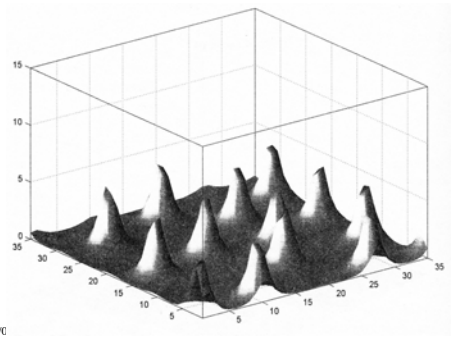


fig. from Solé & Goodwin

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

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

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)