A simple model for the formation of a complex organism

- Characteristics of a complex organism

- Requirements for the formation of a complex organism

- Role of Darwinian evolution and selfish individuals

- A simple model

- Discussion

Characteristics of a complex organism

- Structure on all scales
- Sociology: individuals, families, villages, tribes, countries
- Economy: individuals, groups, companies, trading markets
- Biology: cells, multicellular organisms, populations, ecosystems

Requirements for the formation of a complex organism

- Communication (coming with a cost)

- Specialization

- A quantity that can be increased through this process (fitness, utility, productivity, living standard)

- For large groups communication cost increases faster than productivity

- The result is a hierarchy of groups of interacting units

Role of Darwinian evolution and selfish individuals

- The capacity to communicate and specialize are emergent properties at all organizational levels. It is hard to believe that they should be due to Darwinian selection

- There are many ways in which selfish individuals can be prevented from exploiting the system

  - Classical evolutionary explanations: kin selection, group selection, iterated games

  - In many situations there is no increased payoff for selfish individuals: they exclude themselves; they are punished; they are not admitted; they are suppressed by top–down mechanisms;

A simple model

Productivity of a group of n individuals:

$$P_1(n) = g_1 n(n-1) - c_1 n^2 (n-1)$$

g_1: gain per individual per partner

c_1: communication cost per individual per partner (increases with group size); $c_1 \ll g_1$.

- Optimum group size with largest productivity per individual:

$$n_{opt} = (g_1 + c_1)/2c_1$$

- Maximum possible group size

$$n_{max} = g_1/c_1$$

- Group size above which a split into two independent groups of size $n/2$ increases the productivity:

$$n_{split} = 2(g_1 + c_1)/3c_1$$

Productivity of I interacting groups:

$$P_2(n_1, \ldots, n_I) = \sum_{i=1}^{I} P_1(n_i) + g_2 \sum_{i \neq j} n_i P_1(n_j) - c_2 I(I-1) \sum_{i=1}^{I} n_i$$

g_2: gain per group member per unit of partner productivity

c_2: communication cost per group member per partner group

$g_2 \simeq c_1/g_1$ (of the order $1/n_{opt}$)

$c_2 \simeq g_1(n_i/I)$

The size n of the groups within an optimum supergroup is larger by 4/3 compared to n_{opt} (limit of large n and I).

Approximate productivity of a group of order k:

$$P_k = g_k I_k^2 I_{k-1} P_{k-1} - c_k I_{k-1} I_k^3$$

If

$$g_k \simeq c_1 / g_1$$

and

$$c_k \simeq {g_1}^{2k-3} / {c_1}^{2k-4}$$

(making all I_k of the same order), then

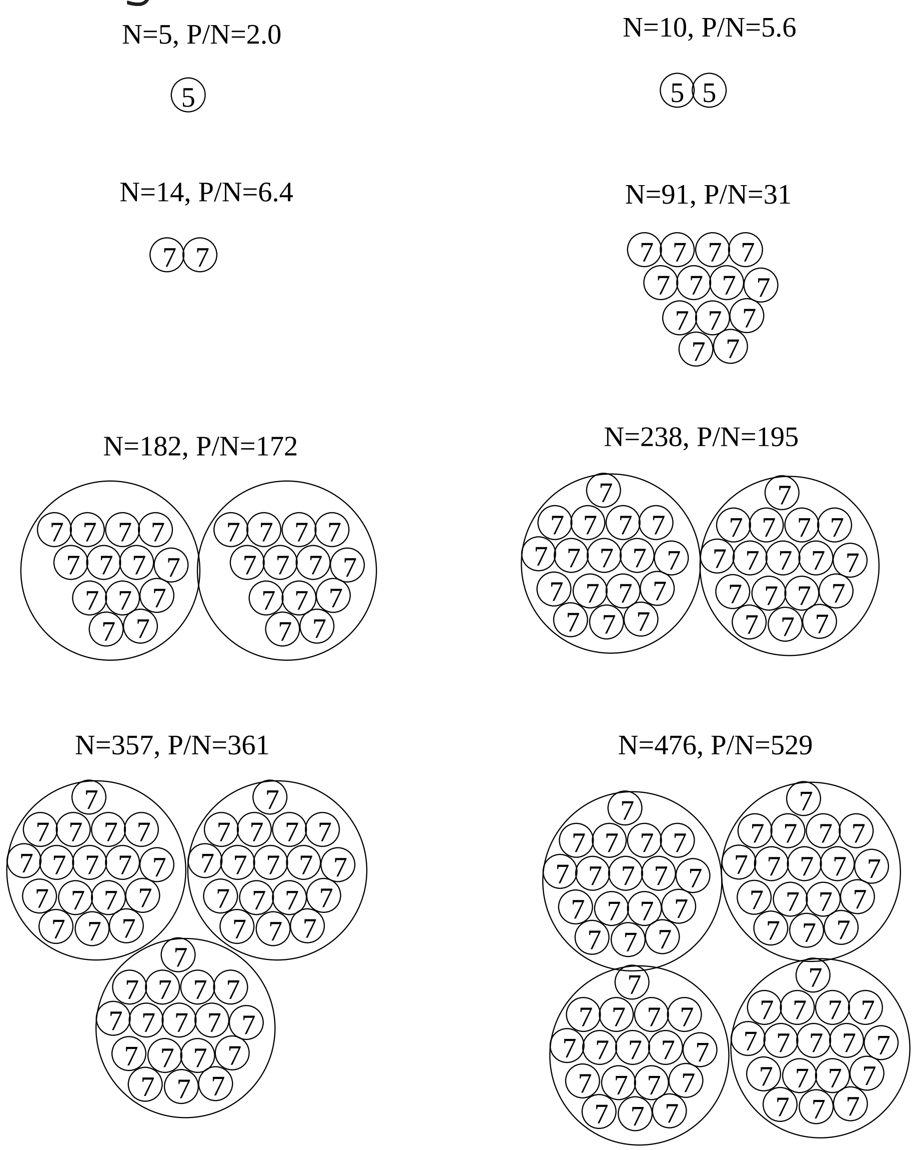
$$P_k \simeq g_1 N^2$$

just as a single large group with no communication cost.

Computer simulations

Realistic groups cannot make a global otimization, but obey local growth rules.

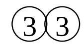
Version 1: Groups grow as long as this increases their productivity; then they start communicating



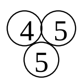
Version 2: Individuals are added one by one. Units can make moves that increase productivity

N=5, P/N=2.0

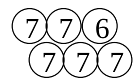
N=6, P/N=2.68



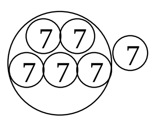
N=14, P/N=7.94



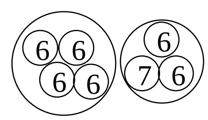
N=41,P/N=20.8



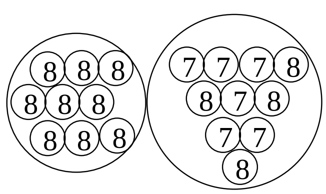
N=42, P/N=21



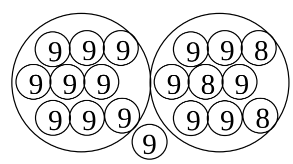
N=43,P/N=25.4



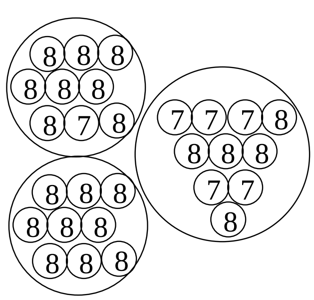
N=146, P/N=116



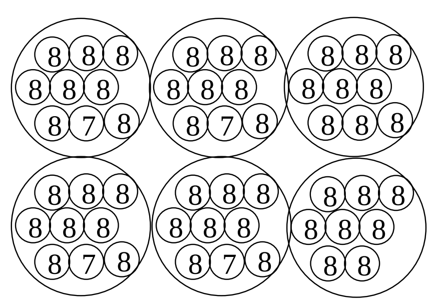
N=168, P/N=60.3



N=N=218, P/N=200



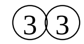
N=420, P/N=426



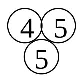
Version 3: Groups rearrange into a different number of groups of equal size

N=5, P/N=2.0

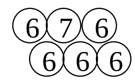
N=6, P/N=2.68



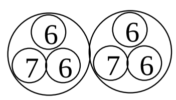
N=14, P/N=7.94



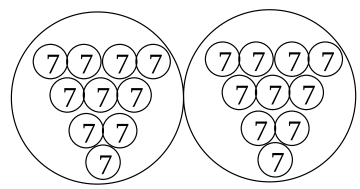
N=37,P/N=20.2



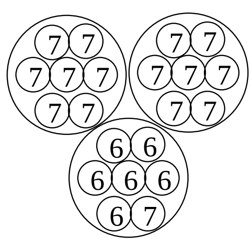
N=38, P/N=20.4



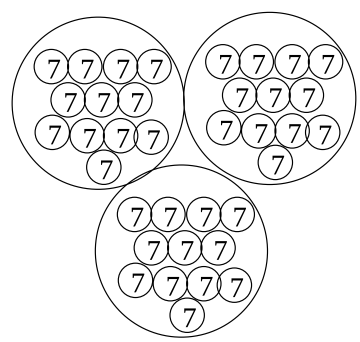
N=140, P/N=131



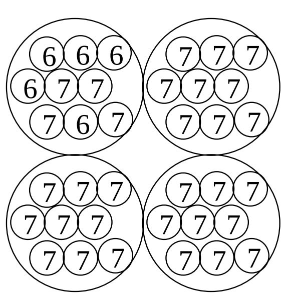
N=141, P/N=133



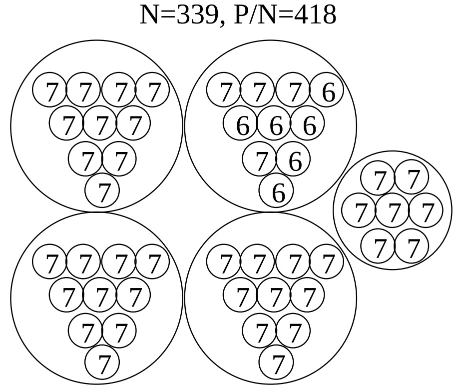
N=246, P/N=280



N=247, P/N=282



N=339, P/N=418



Discussion

- The model illustrates that the ingredients communication and specialization are responsible for the formation of complex organisms

- The simulations show that a complex organism forms under fairly general conditions

- Possible generalizations: unequal individuals, change of parameters with time, spacial degrees of freedom, ...