Collective behaviour

modelling drives

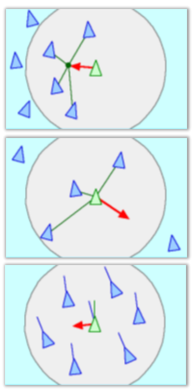
Boids

Reynolds C, 1987

$$\mathbf{F}_\mathrm{A} = \left[\left(\frac{1}{n}\sum_i \mathbf{p}_i\right) - \mathbf{p}\right]^0$$

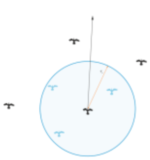
$$\mathbf{F}_\mathrm{R} = \left[\sum_i \frac{\mathbf{p} - \mathbf{p}_i}{\|\mathbf{p} - \mathbf{p}_i\|^2}\right]^0$$

$$\mathbf{F}_\mathrm{P} = \left[\left(\frac{1}{n}\sum_i \mathbf{v}_i\right) - \mathbf{v}\right]^0$$



Stochastic flocks

Heppner FH & Grendander U, 1987



homing

$$\mathbf{F}_\mathrm{H} = \begin{cases} \mathbf{0} & \text{iff } \|\mathbf{r} - \mathbf{p}\| < h_\mathrm{m} \\ \dfrac{c^a e^{-bc}}{(a/b)^a e^{-a}}(\mathbf{r} - \mathbf{p}) & \text{iff } \|\mathbf{r} - \mathbf{p}\| \geq h_\mathrm{m} \end{cases}$$

$$c = \frac{a}{b}\left(\frac{\|\mathbf{r} - \mathbf{p}\| - h_\mathrm{m}}{h_\mathrm{M}}\right)$$

velocity regulation

$$\mathbf{F}_\mathrm{V} = (v_p - \|\mathbf{v}\|)\mathbf{v}^0$$

interaction

$$\mathbf{F}_\mathrm{I} = \sum_i \left[1 - \frac{(\|\mathbf{p}_i - \mathbf{p}\| - a)^2}{b}\right] c(\mathbf{p}_i - \mathbf{p})$$

$$a = \frac{d_\mathrm{p} + r_o}{2}, \qquad b = \left(\frac{d_\mathrm{p} - r_o}{2}\right)^2$$

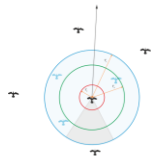
$$c = \begin{cases} 1 & \text{iff } \|\mathbf{p}_i - \mathbf{p}\| \geq d_\mathrm{p} \\ \|\mathbf{p}_i - \mathbf{p}\| \dfrac{(b - a^2) - f_\mathrm{M}}{d_\mathrm{p}(b - a^2)} + \dfrac{f_\mathrm{M} b}{b - a^2} & \text{iff } \|\mathbf{p}_i - \mathbf{p}\| < d_\mathrm{p} \end{cases}$$

distractions

$$\mathbf{F}_\mathrm{D} = \boldsymbol{\xi}^0$$

Collective behaviour of animal groups

Couzin I, *et al*, 2002



repulsion

$$\mathbf{F}_\mathrm{R} = -\sum_{i \in \mathrm{ZOR}} (\mathbf{p}_i - \mathbf{p})^0$$

orientation

$$\mathbf{F}_\mathrm{O} = \sum_{i \in \mathrm{ZOO}} \mathbf{v}_i^0$$

attraction

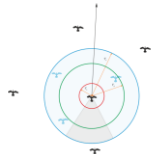
$$\mathbf{F}_\mathrm{A} = \sum_{i \in \mathrm{ZOA}} (\mathbf{p}_i - \mathbf{p})^0$$

action selection

$$\mathbf{F} = \begin{cases} \mathbf{v} & \text{iff ZOR} \cup \text{ZOO} \cup \text{ZOA} = \emptyset \\ \mathbf{F}_\mathrm{R} & \text{iff ZOR} \neq \emptyset \\ \mathbf{F}_\mathrm{O} & \text{iff ZOO} \neq \emptyset \text{ and ZOA} = \emptyset \\ \mathbf{F}_\mathrm{A} & \text{iff ZOO} = \emptyset \text{ and ZOA} \neq \emptyset \\ \dfrac{\mathbf{F}_\mathrm{O} + \mathbf{F}_\mathrm{A}}{2} & \text{iff ZOO} \neq \emptyset \text{ and ZOA} \neq \emptyset \end{cases}$$

Effective leadership and decision making in animal groups on the move

Couzin I, *et al*, 2005



repulsion; ZOR $\neq \emptyset$

$$\mathbf{d}_i(t + \Delta t) = -\sum_{j \neq i} \frac{\mathbf{c}_j(t) - \mathbf{c}_i(t)}{|(\mathbf{c}_j(t) - \mathbf{c}_i(t))|}$$

interaction – attraction and alignment; ZOR $= \emptyset$

$$\mathbf{d}_i(t + \Delta t) = \sum_{j \neq i} \frac{\mathbf{c}_j(t) - \mathbf{c}_i(t)}{|(\mathbf{c}_j(t) - \mathbf{c}_i(t))|} + \sum_{j=1} \frac{\mathbf{v}_j(t)}{|\mathbf{v}_j(t)|}$$

informed group members

proportion of members p given information (unit vector **g**)

$$\mathbf{d}_i{}'(t + \Delta t) = \frac{\hat{\mathbf{d}}_i(t + \Delta t) + \omega \mathbf{g}_i}{|\hat{\mathbf{d}}_i(t + \Delta t) + \omega \mathbf{g}_i|}$$

Effective leadership and decision making in animal groups on the move

Couzin I, *et al*, 2005

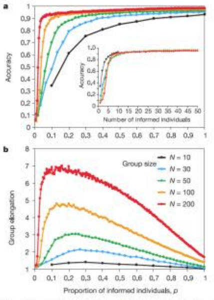


Figure 1 Group accuracy, and shape, as a function of the proportion of informed individuals p, for different group sizes N. The initial increase in accuracy as a function of p (**a**) is associated with the group becoming elongated as p increases (**b**). Informed individuals tend to occupy a frontal position within the group. The elongation of the group then decreases as p increases further and an increasingly large proportion of the group have knowledge of the directional vector **g**. 400 replicates, $\omega = 0.5$; $\alpha = 1$, $\rho = 6$, $\gamma = 0$, $\Delta t = 0.2$ s, $\theta = 2$, $s_i = \alpha$ s^{-1} corresponding to fish[2,19].

Effective leadership and decision making in animal groups on the move

Couzin I, *et al*, 2005

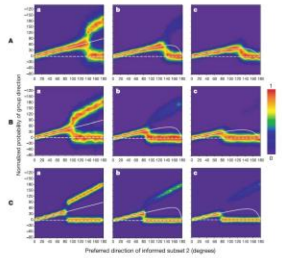


Figure 3 Collective selection of group direction when informed individuals differ in preference. Normalized probability distribution (proportion of maximum) of group direction for groups containing two subsets (with directional preferences $s1$ and $s2$, and of sizes $n1$ and $n2$, respectively) of informed individual within each group, each with its own directional preference: $s1 = 0$ degrees (white dotted line) whereas $s2 = 0$–180 degrees (2,000 replicates per 10-degree interval). Total group size $N = 100$ (parameters as for Fig. 1; ω, $\omega_{max} = 0.4$). We show the large influence of slightly changing $n1$ and $n2$ on group direction. In **a**, the first column, $n1 = n2$ (**A**, **B** = 5; **C** = 10), demonstrating consistency at larger values of p. In **b**, the second column, $n1$ is increased by 1, whereas in **c**, column 3, $n1$ is increased by 1 and $n2$ decreased by 1 (to allow direct comparison with the first column). **B** and **C** include feedback. **A**, **a**, $n1 = 5$, $n2 = 5$; **A**, **b**, $n1 = 6$, $n2 = 5$; **A**, **c**, $n1 = 6$, $n2 = 4$; **B**, **a–c**, $n1$ and $n2$ as for **A**, **a–c**, respectively. **C**, **a**, $n1 = 10$, $n2 = 10$; **C**, **b**, $n1 = 11$, $n2 = 10$. **C**, **c**, $n1 = 11$, $n2 = 9$. For **B** and **C** $\omega_{inc} = 0.012$, $\omega_{dec} = 0.0006$. Solid white lines are for reference only, representing the direction of the average vector **g** of all informed individuals (with constant ω).

An individual based model of fish school reactions: predicting antipredator behaviour as observed in nature

Vabø R & Nøttestad L, 1997

Herring behavioural algorithm

The behaviour of each herring can be described in the following way:

1 Check the surrounding cells within the distance given by the *perception length* and calculate the number of other herring in each different direction.
2 Check if there is a predator in the surrounding cells within the distance given by the *panic distance*.
3 Find the direction which is most preferable according to the attraction strategy. If a predator is found in one direction within the panic distance, the direction opposite to the predator is selected as the most preferable.
4 Move one position to a neighbouring cell in the most preferred direction. If the cell chosen as the new position is already at maximum density, the move is not allowed and the herring must try to move in the second direction of priority and so on.

Predator behavioural algorithm

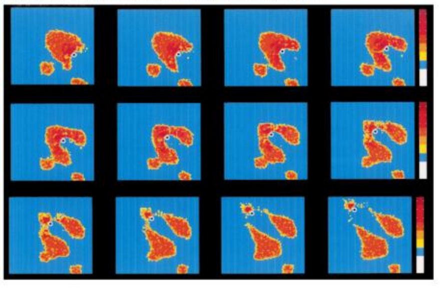
The behaviour of a predator can be modelled in many different ways, depending on what type of predator one wishes to influence the schooling fish. Some predators prefer to attack fish schools peripherally, while others strike in the centre of a school. A single type of predator behaviour was used in the study, with predators having a simple tactic of switching between two modes as follows.

1 Mode 1: Follow blindly a single direction for a certain number of time steps (20–40), then switch to mode 2.
2 Mode 2: When single individual herring are isolated, attack these vulnerable individual herring. Do this for a certain number of time steps, then switch back to mode 1.

An individual based model of fish school reactions: predicting antipredator behaviour as observed in nature

Vabø R & Nøttestad L, 1997

Figure 8. Split and join behaviour including herd, fountain and isolation of individual herring during predator attack. Parameter settings: t = timestep of approximately one second. (a_1 to a_{12}): Grid size, $N = 60 \times 60$, $LH = 8$, $D = 5$ (6), $NI = 1800$, $LP = 50$, $PD = 8$. Note that a join is not completed in the end of this series, although in progress. The high PD is the main reason for the splitting seen in this example. The predator is indicated as the black dot.



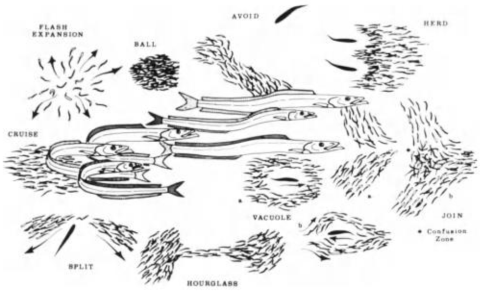


Fig. 2. Schematic diagram of the predator-avoidance tactics observed in sand-eel schools. Cruise was the undisturbed baseline state of the school. Vacuole is illustrated in two orientations: (a) where the predator is swimming in the same direction as the sand-eels, and (b) the reverse. We have no direct evidence that Ball was a response to the mackerel predators in the tank experiment. (Note: tactics are drawn schematically seen from above: sand-eels drawn from side in 'foreground' are for purposes of illustration only).

Pitcher TJ & Wyche CJ, 1983 doi: 10.1007/978-94-009-7296-4_21

Self-Organized Shape and Frontal Density of Fish Schools

Hemelrijk CK & Hildenbrandt H, 2008

adaptive perception radius

$$R_i' = R_{max} - n_w \cdot n(t)$$

$$R_i(t+\Delta t) = max\{R_{min}, (1-s)\cdot R(t) + s.R'\};\ s = n_i \cdot \Delta t$$

separation

$$\boldsymbol{d}_{si} = -\frac{1}{n_s}\sum_{j=1}^{n_s}\frac{\boldsymbol{r}_{ij}}{|\boldsymbol{r}_{ij}|^2};\ f_{si} = w_s\frac{\boldsymbol{d}_{si}}{|\boldsymbol{d}_{si}|}$$

alignment

$$\boldsymbol{d}_{ai} = -\frac{1}{n_a}\sum_{j=1}^{n_a}\boldsymbol{e}_{xj};\ \boldsymbol{f}_{ai} = w_a\frac{\boldsymbol{d}_{ai}-\boldsymbol{e}_{xi}}{|\boldsymbol{d}_{ai}-\boldsymbol{e}_{xi}|}$$

cohesion

$$\boldsymbol{d}_{ci} = -\frac{1}{n_c}\sum_{j=1}^{n_c}\frac{\boldsymbol{r}_{ij}}{|\boldsymbol{r}_{ij}|};\ \boldsymbol{f}_{ci} = w_c\frac{\boldsymbol{d}_{ci}}{|\boldsymbol{d}_{ci}|}$$

speed regulation

$$\boldsymbol{f}_{speedi} = \frac{1}{\tau}(v_0 - v)\boldsymbol{e}_{xi}$$

levelling

$$\boldsymbol{f}_{pci} = -w_{pc}(\boldsymbol{e}_{xi}\cdot z)z;\ \boldsymbol{f}_{rci} = -w_{rc}(\boldsymbol{e}_{yi}\cdot z)z.$$

action selection

$$\boldsymbol{f}_{neti} = \{\boldsymbol{f}_{si} + \boldsymbol{f}_{ai} + \boldsymbol{f}_{ci} + \boldsymbol{f}_{speedi} + \boldsymbol{f}_{pci} + \boldsymbol{f}_{rci} + \boldsymbol{f}_{\zeta}\}.$$

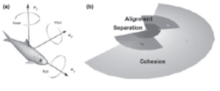


Fig. 1: (a) Local coordinate system. (b) Behavioural zones of separation, alignment and cohesion

Self-Organized Shape and Frontal Density of Fish Schools

Hemelrijk CK & Hildenbrandt H, 2008

Table 1: Summary of model parameters. The unit of length is one body length (BL) and the unit of mass is one body mass (BM)

Parameter	Unit	Symbol	Value(s) explored
Number of individuals	1	N	10-2000
Time step	s	Δt	0.05
Zone of separation			
Radius	BL	R_{min}	2
Blind angle back	Degrees	–	60
Zone of alignment			
Maximum Radius	BL	–	5 (adaptive)
Blind angle back	Degrees	–	60
Blind angle front	Degrees	–	60
Zone of cohesion			
Maximum Radius	BL	R_{max}	15 (adaptive)
Blind angle back	Degrees	–	90
Cruise speed	BL/s	v_0	2; 4
Weights			
Separation	$BL^2 \cdot BM/s^2$	w_s	10
Alignment	BM/s^2	w_a	5
Cohesion	BM/s^2	w_c	9
Relaxation time	s	τ	0.2
Pitch control	$BL^2 \cdot BM/s^2$	w_{pc}	2
Roll control	$BL^2 \cdot BM/s^2$	w_{rc}	5
Random noise	$BL^2 \cdot BM/s^2$	$|f_\zeta|$	0.5
Max. force	$BL^2 \cdot BM/s^2$	f_{max}	3

Self-Organized Shape and Frontal Density of Fish Schools

Hemelrijk CK & Hildenbrandt H, 2008

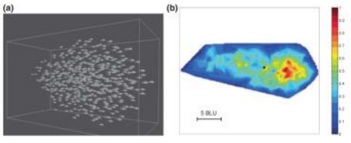


Fig. 2: (a) Typical snapshot of the school within the bounding box. (b) Density distribution of its members. The school consists of 600 individuals that are moving at 2 BL/s. The stars indicate the locations of the centre of gravity. The density distribution is measured as the number of individuals in the cohesion region (BL^{-3}).

Social forces

Helbing D & Molnár P, 1995

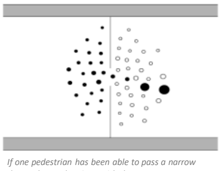
$$\vec{F}_\alpha(t) := \vec{F}_\alpha^0(\vec{v}_\alpha, v_\alpha^0\vec{e}_\alpha) + \sum_\beta \vec{F}_{\alpha\beta}(\vec{e}_\alpha, \vec{r}_\alpha - \vec{r}_\beta) + \sum_B \vec{F}_{\alpha B}(\vec{e}_\alpha, \vec{r}_\alpha - \vec{r}_B^\alpha) + \sum_i \vec{F}_{\alpha i}(\vec{e}_\alpha, \vec{r}_\alpha - \vec{r}_i, t)\,.$$

The *social force model* is now defined by

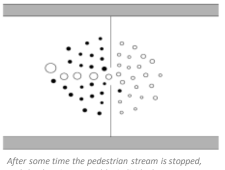
$$\frac{d\vec{w}_\alpha}{dt} := \vec{F}_\alpha(t) + \textit{fluctuations}.$$

Social forces

Helbing D & Molnár P, 1995



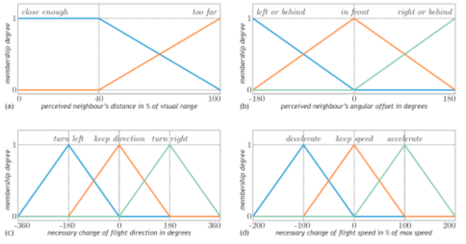
If one pedestrian has been able to pass a narrow door, other pedestrians with the same desired walking direction can follow easily whereas pedestrians with an opposite desired direction of motion have to wait. The diameters of the circles are a measure for the actual velocity of motion.



After some time the pedestrian stream is stopped, and the door is captured by individuals who pass the door into the opposite direction.

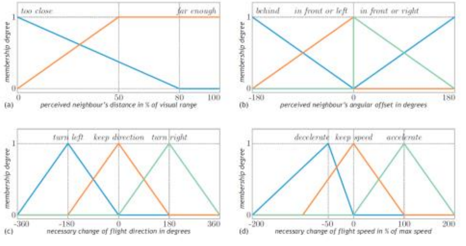
Simulating flocks on the wing: the fuzzy approach

Lebar Bajec I, *et al*, 2005



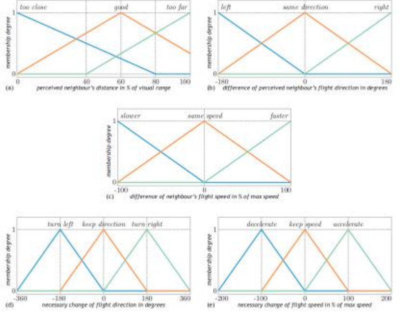
Simulating flocks on the wing: the fuzzy approach

Lebar Bajec I, *et al*, 2005



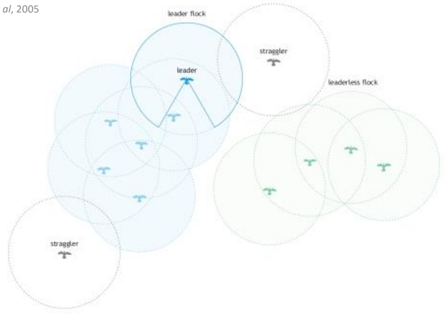
Simulating flocks on the wing: the fuzzy approach

Lebar Bajec I, *et al*, 2005



Simulating flocks on the wing: the fuzzy approach

Lebar Bajec I, *et al*, 2005



Verifikacija?

Huepe C & Aldana M, 2008

$$\psi(t) = \frac{1}{Ns}\left|\sum_{i=1}^{N} \vec{\mathrm{V}}\mathrm{el}[\theta_i(t)]\right|$$

$$\tilde{\rho}(t) = \langle \mathrm{C_n}[Z_i(t)]\rangle_i$$

$$\tilde{\delta} = \left\langle \min\left(\left|\vec{x}_j - \vec{x}_i\right|_{j \in Z_i}\right)\right\rangle_i$$