

Self-organizing pedestrian movement

Dirk Helbing, et al.
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Presenter: Jin H. Park
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- ◆ Trail formation
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1. Introduction(1/3)

- ◆ “Although pedestrians have individual preferences, aims, and destinations, the dynamics of pedestrian crowds is predictable”
- ◆ “Systems of pedestrian trails evolve over time”

1. Introduction(2/3)

◆ Empirical study on pedestrian crowds

- Evaluation method based on direct observation, photographs, and time-lapse films
- Objectives
 - ◆ Behavioral investigations
 - ◆ To develop a level-of-service concept, design elements of pedestrian facilities, or planning guidelines

◆ Guidelines with the form of regression relations

- Not suitable for buildings and areas with exceptional architecture

1. Introduction(3/3)

◆ Simulation models

- E.g. queuing models, transition matrix models, stochastic models, route choice behavior models
- Incapable of explaining self-organization effects
 - ◆ Gas, fluid dynamics model?
 - No, either: Lack of interaction such as deceleration maneuver and avoidance
 - ◆ Behavioral force model (Helbing et al.)

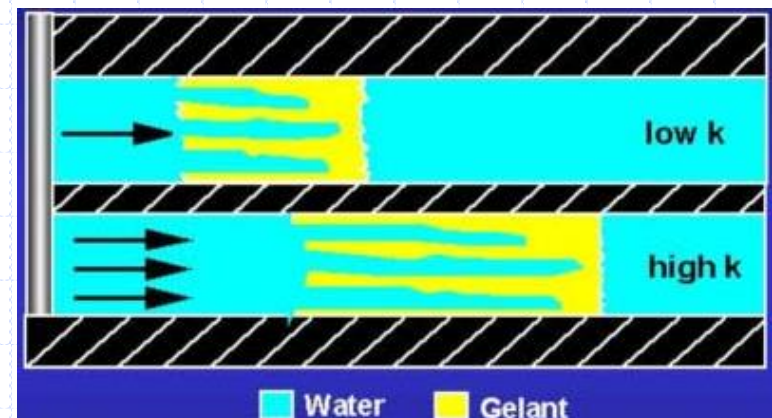
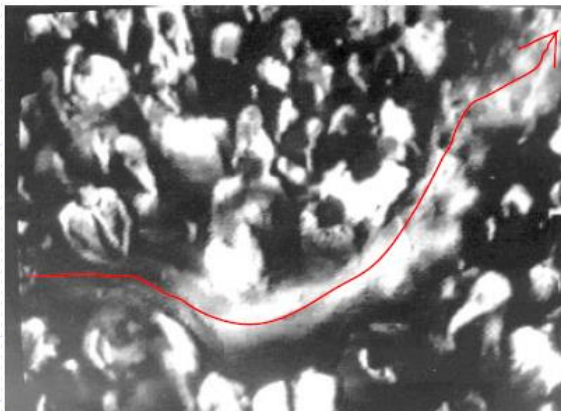
2.Observations(1/3)

- ◆ Strong aversion to take detours or moving opposite to the desired walking direction, even if the direct route is crowded.
→ 'hysteresis effects'
- ◆ Preference of walking with an individual desired speed.
 - desired speed = most comfortable speed = least energy-consuming speed = $N(1.34\text{m/s}, 0.26^2\text{m/s})$
- ◆ Keeping a certain distance from other pedestrians and borders → density
 - ↑ : around particularly attractive places
 - ↓ : growing velocity variance
- ◆ Not reflecting their behavioral strategy in every situation anew but acting somewhat automatically

2.Observations(2/3)

◆ Similarities with fluids at medium and high pedestrian densities

- Footsteps of pedestrians → streamlines of fluids
- Borderline shape between opposite directions of walking → Viscous fingering
- Crossing stationary crowds → river-line streams
- The propagation of shockwaves



2.Observations(3/3)

◆ Similarities with granular flows

- The flow on the diameter of the street does not obey the Hagen Poiseuille law.

$$Q = \frac{\pi a^4}{8} \cdot \frac{P1 - P2}{\eta l}$$



- Pedestrians spontaneously organize themselves in lanes of uniform walking direction, if the pedestrian density is high enough
- The passing direction of pedestrians oscillates with a frequency that increases with the width and shortness of the bottleneck.

3. Behavioral Force Model(1/12)

- ◆ “Behavioral changes are guided by so-called social fields or social forces” (Lewin, 1951)
- ◆ mathematical representation by Helbing (1994; 1995).

$$\frac{dr_{\alpha}(t)}{dt} = v_{\alpha}(t)$$

$$\frac{dv_{\alpha}}{dt} = f_{\alpha}(t) + \xi_{\alpha}(t)$$

$r_{\alpha}(t)$: position of a pedestrian α at time t

$f_{\alpha}(t)$: social force, $\xi_{\alpha}(t)$: variation

3. Behavioral Force Model(2/12)

$$\mathbf{f}_\alpha(\mathbf{t}) = \mathbf{f}_\alpha^0(\mathbf{v}_\alpha) + \mathbf{f}_{\alpha B}(\mathbf{r}_\alpha) + \sum_{\beta(\neq \alpha)} \mathbf{f}_{\alpha\beta}(\mathbf{r}_\alpha, \mathbf{v}_\alpha, \mathbf{r}_\beta, \mathbf{v}_\beta) + \sum_i \mathbf{f}_{\alpha i}(\mathbf{r}_\alpha, \mathbf{r}_i, \mathbf{t}) + \xi_\alpha(\mathbf{t})$$

$$\mathbf{f}_\alpha^0(\mathbf{v}_\alpha) = \frac{1}{\tau_\alpha} (\mathbf{v}_\alpha^0 \mathbf{e}_\alpha - \mathbf{v}_\alpha) = \frac{1}{\tau_\alpha} (\mathbf{v}_\alpha^0 - \mathbf{v}_\alpha) : \text{desired acceleration force}$$

$\mathbf{v}_\alpha^0$: desired individual speed

$\mathbf{e}_\alpha$: desired direction for the next goal

$\mathbf{v}_\alpha$: actual velocity

τ_α : relaxation time

3. Behavioral Force Model(3/12)

$$\mathbf{f}_{\alpha}(\mathbf{t}) = \mathbf{f}_{\alpha}^0(\mathbf{v}_{\alpha}) + \mathbf{f}_{\alpha B}(\mathbf{r}_{\alpha}) + \sum_{\beta(\neq \alpha)} \mathbf{f}_{\alpha\beta}(\mathbf{r}_{\alpha}, \mathbf{v}_{\alpha}, \mathbf{r}_{\beta}, \mathbf{v}_{\beta}) + \sum_i \mathbf{f}_{\alpha i}(\mathbf{r}_{\alpha}, \mathbf{r}_i, \mathbf{t}) + \xi_{\alpha}(\mathbf{t})$$

$\mathbf{f}_{\alpha B}(\mathbf{r}_{\alpha}) = -\nabla_{\mathbf{r}_{\alpha}} V_B(||\mathbf{r}_{\alpha} - \mathbf{r}_B^{\alpha}||)$: a repulsive force by border B

V_B : a repulsive potential

$||\mathbf{r}_{\alpha} - \mathbf{r}_B^{\alpha}||$: the distance between the position of α
and the nearest point $\mathbf{r}_B^{\alpha}$ of the border

$\mathbf{f}_{\alpha\beta}(\mathbf{r}_{\alpha}, \mathbf{v}_{\alpha}, \mathbf{r}_{\beta}, \mathbf{v}_{\beta})$: a repulsive force by neighbors

$\mathbf{f}_{\alpha\beta}(\mathbf{r}_{\alpha}, \mathbf{r}_i, \mathbf{t})$: a attractive force

$\xi_{\alpha}(\mathbf{t})$: variation

3. Behavioral Force Model(4/12)

◆ Explaining observations by equilibria

1) sitting with uniform distribution

$$\sum_{\beta(\neq\alpha)} f_{\alpha\beta}(\mathbf{r}_{\alpha}, \mathbf{v}_{\alpha} = 0, \mathbf{r}_{\beta}, \mathbf{v}_{\beta} = 0) = 0$$

2) More crowd regions close to the attractions

$$\sum_{\beta(\neq\alpha)} f_{\alpha\beta}(\mathbf{r}_{\alpha}, \mathbf{v}_{\alpha} = 0, \mathbf{r}_{\beta}, \mathbf{v}_{\beta} = 0) + \sum_i f_{ai}(\mathbf{r}_{\alpha}, \mathbf{r}_i, t) = 0$$

3) calculating required time to join an attraction

$$\frac{\mathbf{v}_{\alpha}^0(t) - 0}{\tau_{\alpha}} + f_{ai}(\mathbf{r}_{\alpha}, \mathbf{r}_i, t) = 0$$

3. Behavioral Force Model(5/12)

4) pushing behavior

$$\frac{1}{\tau_{\alpha}}(v_{\alpha}^0 \mathbf{e}_{\alpha} - \mathbf{v}_{\alpha}) + \mathbf{f}_{\alpha\beta}(\mathbf{r}_{\alpha}, \mathbf{v}_{\alpha}, \mathbf{r}_{\beta}, \mathbf{v}_{\beta}) = 0, \quad \mathbf{v}_{\alpha}^0 = v_{\alpha}^0 \mathbf{e}_{\alpha}$$
$$\frac{\mathbf{v}_{\alpha}^0 - \mathbf{v}_{\beta}}{\tau_{\alpha}} + \mathbf{f}_{\alpha\beta}(\mathbf{r}_{\alpha}, v_{\beta} \mathbf{e}_{\alpha}, \mathbf{r}_{\alpha} + \|\mathbf{r}_{\beta} - \mathbf{r}_{\alpha}\| \mathbf{e}_{\alpha}, v_{\beta} \mathbf{e}_{\alpha}) = 0$$

τ_{α} : the 'acceleration time' to reach the desired velocity

5) model parameters specifying

$$\frac{v_{\alpha}^0}{\tau_{\alpha}} \approx \frac{v_{\beta}^0}{\tau_{\beta}}, \text{ an example}$$

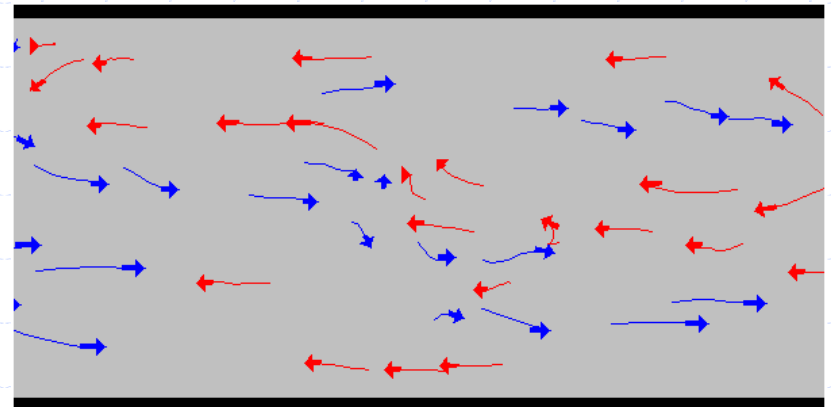
3. Behavioral Force Model(6/12)

- ◆ Reproducing observations by simulation
 - Self-organizing
 - ◆ not externally planned, prescribed, or organized
 - ◆ “The spatiotemporal patterns emerge through the nonlinear interactions of pedestrians”
 - 3 symmetry-breaking self-organizing effects
 - ◆ Formation of lanes
 - ◆ Oscillatory changes at narrow passage
 - ◆ Unstable roundabout traffic

3. Behavioral Force Model(7/12)

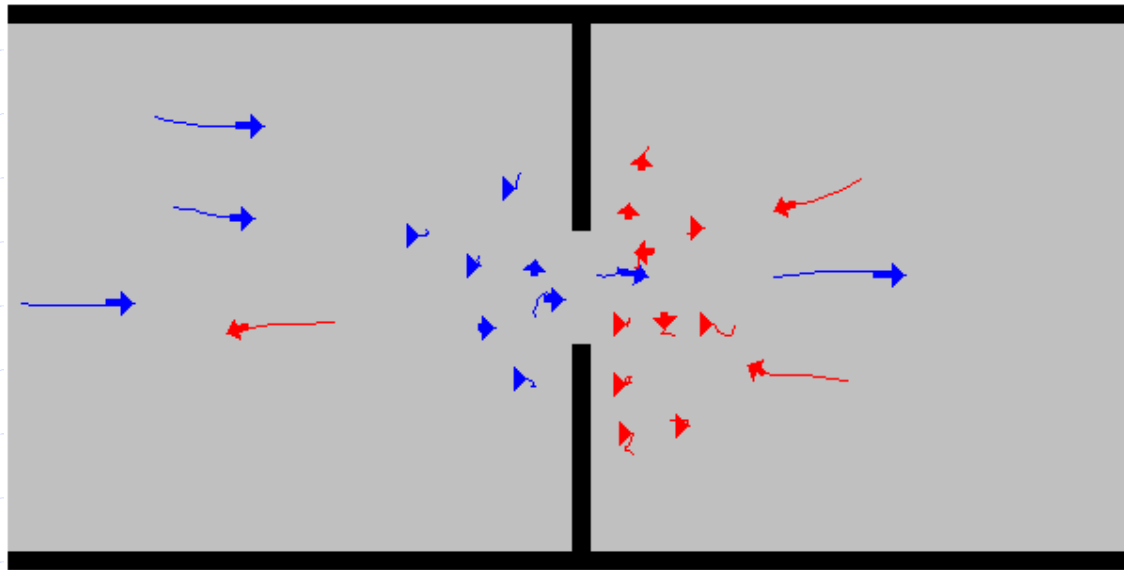
1) Formation of lanes

- consisting of pedestrians with the same desired walking direction
- Without assuming preference for any side
- Minimal interaction rate/maximum efficiency of motion
- Emergence situation
 - ◆ Higher fluctuation strength
 - ◆ "Freeze by heating"
 - ◆ Different parameters



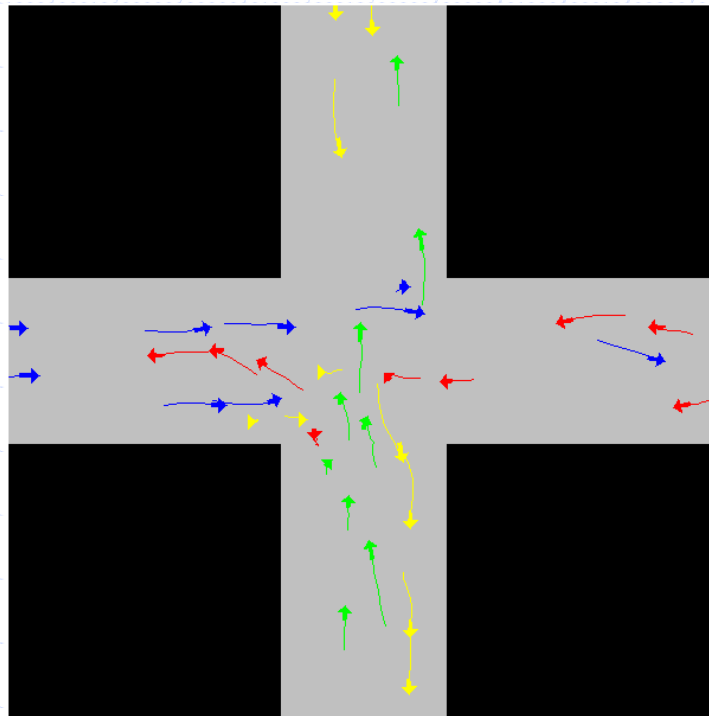
3. Behavioral Force Model(8/12)

2) Oscillatory changes in the walking direction in narrow passage



3. Behavioral Force Model(9/12)

3) Unstable roundabout traffic



3. Behavioral Force Model(10/12)

◆ Optimization of pedestrian facilities

- “The emerging pedestrian flows depend decisively on the geometry of the boundaries”
- Evolutionary algorithms
- Varying parameters
 - ◆ The location and form of planned buildings
 - ◆ The arrangement of walkways, entrances, exits, staircases, elevators, escalators, and corridors
 - ◆ The shape of rooms, corridors, entrances, and exits
 - ◆ The function and time schedule of room usage

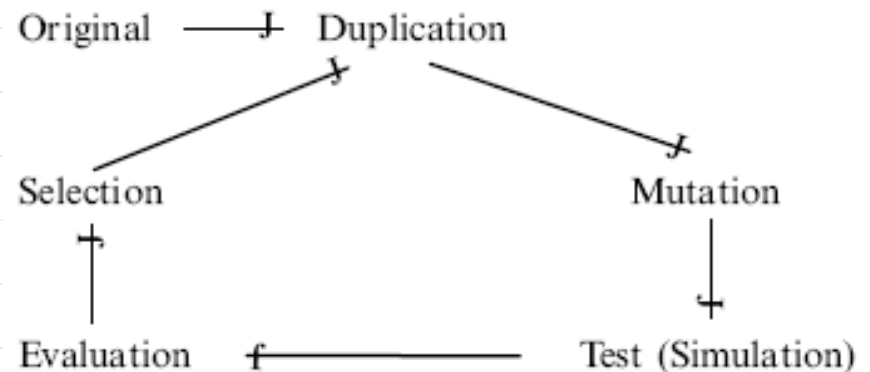
3. Behavioral Force Model(11/12)

■ Mathematical performance measures

$$E = \frac{1}{N} \sum_{\alpha} \frac{\overline{\mathbf{v}_{\alpha} \mathbf{e}_{\alpha}}}{\|\mathbf{v}_{\alpha}^0\|}, \quad 0 \leq E \leq 1$$

$$D = \frac{1}{N} \sum_{\alpha} \frac{\overline{(\mathbf{v}_{\alpha} - \overline{\mathbf{v}_{\alpha}})^2}}{(\overline{\mathbf{v}_{\alpha}})^2} = \frac{1}{N} \sum_{\alpha} \left(1 - \frac{\overline{\mathbf{v}_{\alpha}^2}}{(\overline{\mathbf{v}_{\alpha}})^2} \right), \quad 0 \leq D \leq 1$$

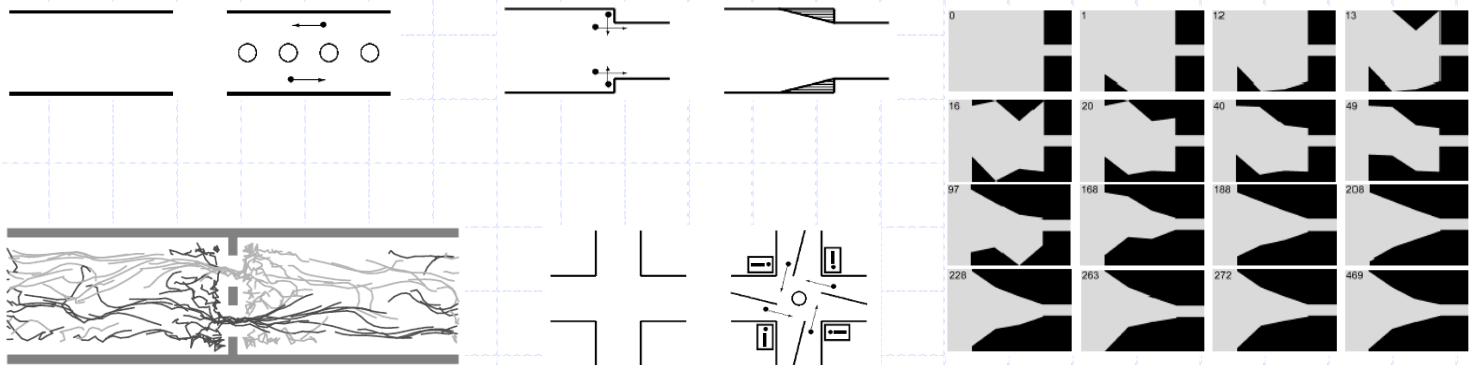
$$C = 1 - D$$



3. Behavioral Force Model(12/12)

■ Optimization examples

- ◆ Lane stabilizing by series of columns in the middle of the road
- ◆ Improving bottleneck by a funnel-shaped construction
- ◆ Two doors rather than a double-sized door
- ◆ Stabilizing roundabout traffic by planting a tree in the middle of a crossing



4.Trail Formation(1/5)

- ◆ Why do pedestrians sometimes build trails in order to save 3 to 5 m, but in other cases accept detours which are much larger?
- ◆ How and by which mechanism do trail systems evolve in space and time?
- ◆ Why do trails reappear at the same places, even if they were destroyed?
- ◆ How should urban planners design public way systems so that walkers actually use them?



4.Trail Formation(2/5)

◆ Active walker model

■ Environmental changes by pedestrian

$$\frac{dG(\mathbf{r},t)}{dt} = \frac{1}{T(\mathbf{r})} [G_0(\mathbf{r}) - G(\mathbf{r},t)] + I(\mathbf{r}) \left[1 - \frac{G(\mathbf{r},t)}{G_{max}(\mathbf{r})} \right] \sum_{\alpha} \delta[\mathbf{r} - \mathbf{r}_{\alpha}(t)]$$

$G(\mathbf{r},t)$: ground structure reflecting the comport of walking

$T(\mathbf{r})$: durability of trails, $1/T(\mathbf{r})$ means a weathering rate

$G_0(\mathbf{r})$: natural ground condition

$I(\mathbf{r})$: intensity of footprint being left by pedestrians at place $\mathbf{r}$

$\delta(\mathbf{r} - \mathbf{r}_{\alpha})$: Dirac delta function

4.Trail Formation(3/5)

- Environment's influence on pedestrian

$$f_{tr}(r_\alpha, t) = \int d^2r \frac{e^{-\frac{||r-r_\alpha||}{\sigma(r_\alpha)}}}{2\pi[\sigma(r_\alpha)]^2} G(r, t) \frac{r - r_\alpha}{||r - r_\alpha||}$$

$f_{tr}(r_\alpha, t)$: overall attractive effect of available trails

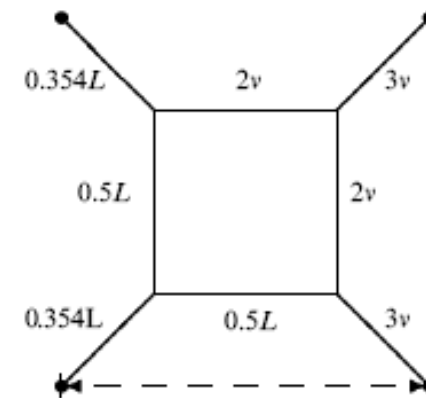
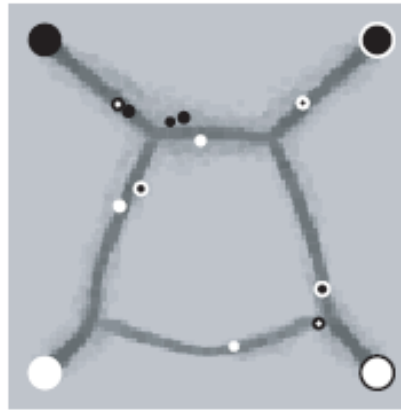
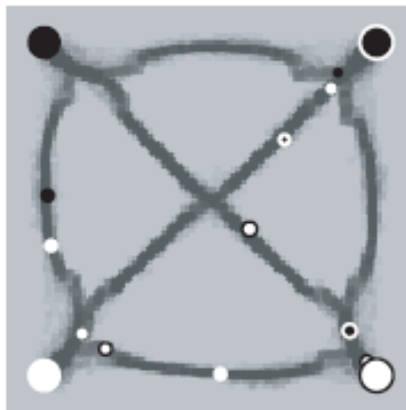
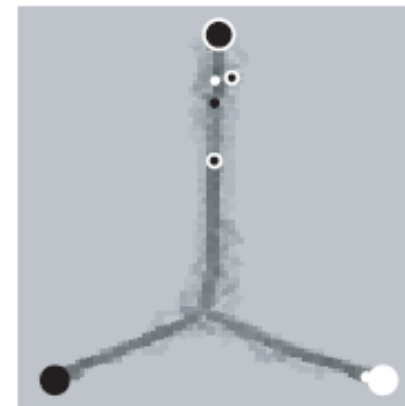
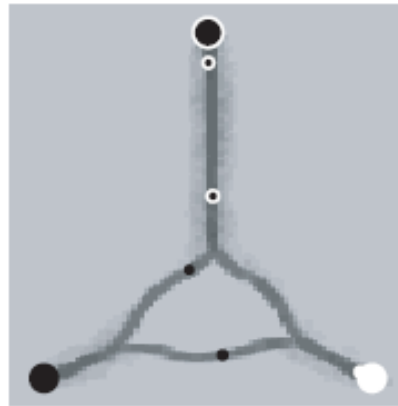
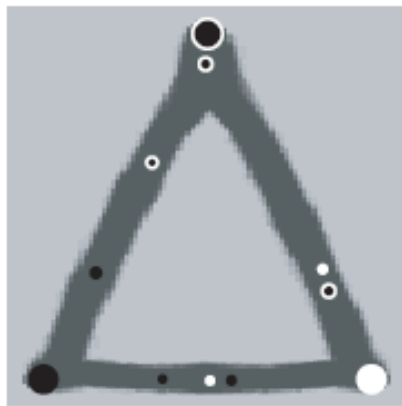
$$e_\alpha^0(r_\alpha) = \frac{d_\alpha - r_\alpha}{||d_\alpha - r_\alpha||}, \quad e_\alpha(r_\alpha, t) = \frac{e_\alpha^0(r_\alpha) + f_{tr}(r_\alpha, t)}{||e_\alpha^0(r_\alpha) + f_{tr}(r_\alpha, t)||}$$

d_α : next destination, e_α : the walking direction

$$e_{tr} = \frac{f_{tr}}{||f_{tr}||}, \quad \frac{dr_\alpha}{dt} = v_\alpha^0(r_\alpha, t) + \zeta_\alpha(t)$$

e_{tr} : the most attractive walking direction

4.Trail Formation(4/5)



4.Trail Formation(4/5)

◆ Optimization of way systems

- Which is the trail system that pedestrians would naturally use?
→ realistic values of l and k
- Is the resulting way system structurally stable with respect to small changes in parameters l and k ?
→ slightly modified parameter values and check.
- Given a certain amount of money to build a way system of a certain length, which one is most comfortable or 'intelligent'?
→ Control the overall length of the evolving way system by variation of k , until it fits the desired length.

4.Trail Formation(5/5)

◆ Optimization of way systems

- If a certain level of comfort is to be provided, which is the cheapest way system satisfying this demand?
→ Increase k , starting with small values, until pedestrians take the average relative detour, which was specified to be acceptable.
- Given an existing way system, how should it be extended?
→ Take into account the existing way system by setting $G_0(r)$.
 G_{max} and check where the resulting way system contains additional trails.

5. Conclusions

- ◆ Pedestrian dynamics shows various collective phenomena.
- ◆ Empirical findings can be described realistically by microscopic simulations of pedestrian streams based on a behavioral force model.
- ◆ Motion can be interpreted as self-organization phenomena, arising from the nonlinear interactions among pedestrians
- ◆ Self-organization flow patterns can significantly change the capacities of pedestrian facilities.
- ◆ Improvements of way systems can be worked out with an active walker model of human trail formation.