Agents Heterogeneity in Microscopic Models of Pedestrian Flow

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Machine Learning and Modelling Seminar
Thursday April 27, 2023

Outline

Pedestrian and Evacuation Dynamics

Description, modelling, and analysis of

Evacuation

Non-emergent egress

Pedestrian traffic

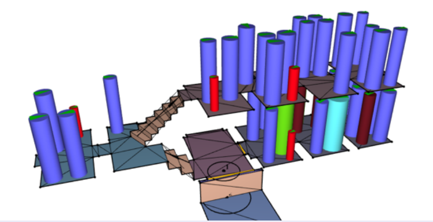
Application in safety management

- Estimation of total evacuation time (TET).
- Estimation of space usage.
- Estimation of bottleneck capacity.
- Identification of problematic areas, bottlenecks, ...

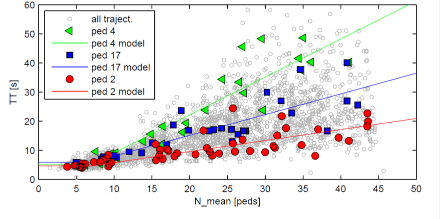
PED – a Multidisciplinary Field

Experimental studies and data-mining

Agent-based modelling



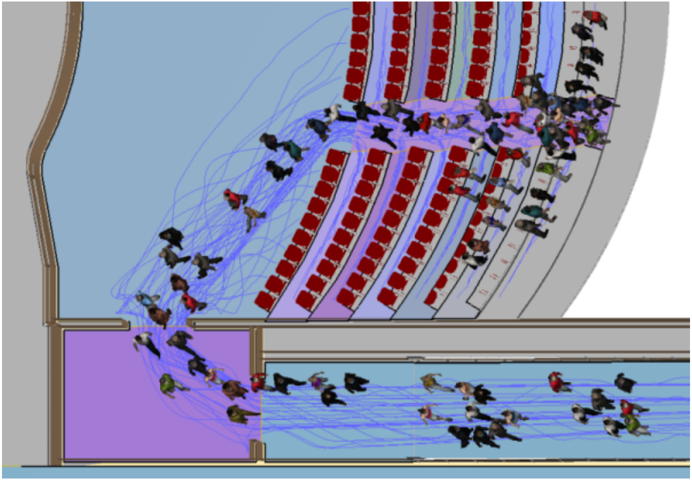
Statistical analysis and modelling



Statistical physics

−4	−3	−2	−1	0	1	2	3	4
0	F	0	0	L	0	1	1	0
0	F	0	0	0	L	1	1	0
0	0	F	0	0	L	1	0	1
0	0	0	F	0	L	0	1	0
1	0	0	0	F	0	L	0	1
1	0	0	0	F	0	0	L	0
0	1	0	0	F	0	0	0	L
0	1	0	0	0	F	0	0	L

Multi-Agent Models of Pedestrian Dynamics


[1]

[1] PathFinder, Thunderhead eng.

Social Force Model for Pedestrian Dynamics

Dirk Helbing and Péter Molnár. Phys. Rev. E 51 (1995)

Newtonian equations of motion

$$\ddot{\vec{x}}_\alpha(t) = \vec{F}_\alpha^{(\mathrm{mot})} + \vec{F}_\alpha^{(\mathrm{int})} + \vec{F}_\alpha^{(\mathrm{env})} + \vec{F}_\alpha^{(\mathrm{ext})}$$

- Attraction to the exit

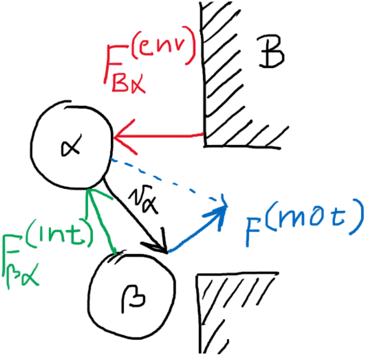
$$\vec{F}_\alpha^{(\mathrm{mot})} \propto v_\alpha^0 \vec{e}_\alpha - \vec{v}_\alpha$$

- Repulsion from others

$$\vec{F}_\alpha^{(\mathrm{int})} = \sum_{\beta \neq \alpha} \vec{F}_{\beta\alpha}^{(\mathrm{int})}$$

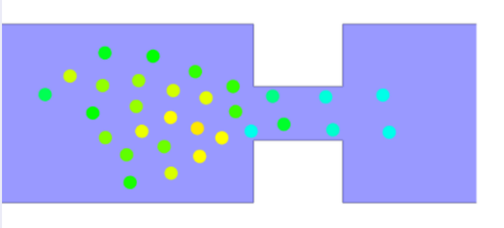
- Repulsion from obstacles

$$\vec{F}_\alpha^{(\mathrm{env})} = \sum_{B} \vec{F}_{B\alpha}^{(\mathrm{env})}$$



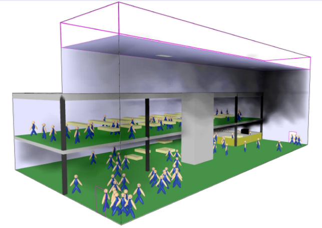
Implementation of Social Force Concept

JuPedSim – open-source simulator from JSC



- Generalized Centrifugal Force Model
- Collision-free Speed Model
- Collision avoidance left to the “Forces”

FDS+Evac – commercial evacuation software

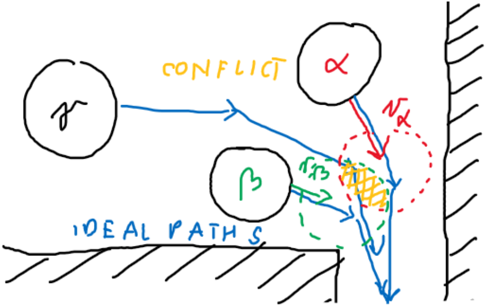


- Helbing Social-Force model
- Collison avoidance rules added
- Fire and human interaction

Path-Navigation and Floor-Field models

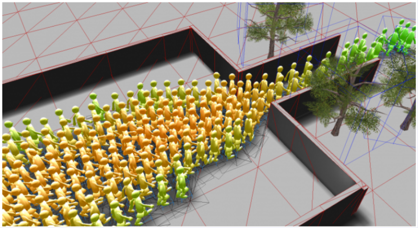
Navigation + Avoiding colissions + Solving conflicts

- Agent chooses direction along ideal path (navigation mesh, potential gradient).
- Agent adjusts its speed based on state of the neighbourhood (obstacles, density, other agents).
- Agents choosing to enter the same cell "negotiate".



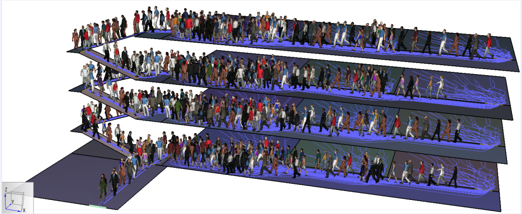
Implemtation of Path-Navigation Models

VADERE – open-source simulator from Munich University of Applied Sciences



- Optimal Steps Model
- Behavioral Heuristics Model
- Navigation using floorfield potential

PathFinder – commercial evacuation software from Thunderhead eng.

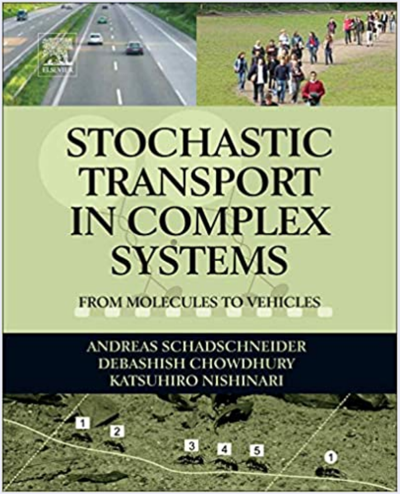


- Path navigating concept
- Navigation mesh
- Collision avoidance + conflict solution algorithm

Cellular Models

- Particles/agents hopping along discrete lattice
- Related to cellular automata
- Inspired by 2D lattice-gas models
- Discrete configuration space
- Popular among statistical physicists
- Rule-based dynamics

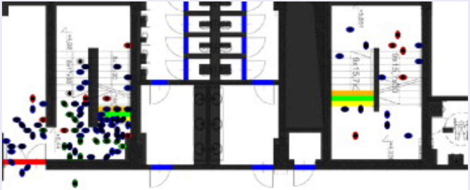
Models and theory (2010)



Latest review: Li et al. A review of cellular automata models for crowd evacuation. Phys. A 526, 120752, 2019

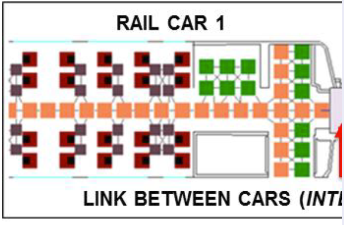
Implementation of Cellular Models

Social Distance Model – academic model from AGH University, Kraków



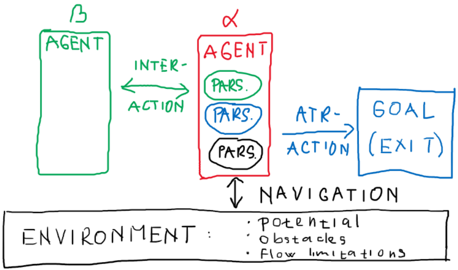
- Allianz Arena Munich, Wisla Krakow
- Finer lattice + Proxemics inspired repulsion

Exodus – commercial evacuation software from University of Greenwich



- BuildingExodus, TrainExodus, PlainExodus, ...
- Strictly rule based
- Waiting times and similar from measurements

Agent in the Model



- Spatial information
- Motivation to reach final destination
- Avoiding collisions
- Interaction
- Movement strategies
- Parameters

Settup of agent-based model

- Consistent with observations
- Calibrated and validated by experimental/field studies
- Providing sufficiently detailed information
- Parameters dedicated to agents, not whole model

Heterogeneity in Pedestrian Evacuation Model

Variance of parameters

- Desired velocity

$$v_\alpha^0 \sim \mathcal{N}(\mu_v, \sigma_v^2)$$

- Agent radius/shape

$$R_\alpha \sim \mathcal{N}(\mu_v, \sigma_R^2)$$

- Acceleration parameters

$$a_\alpha \sim \mathcal{U}(a_{\min}, a_{\max})$$

Different abilities

- Adults, Children, Seniors
- Without or with limitation
- Needing assistance

- Heterogeneity of crowd often neglected
- Draws attention recently
- Focus on vulnerable evacuees

Is heterogeneity important?

- Does it bring anything new?
- Crowd modelled by identical agents with average properties – is it the same?
- How to implement it?

Outline

Crowd Dynamics Experiment

- Alternative to empirical measurements
- Conducted experiments, field studies, evacuation drills
- Important to understand the human behaviour and interaction
- A lot of various experiments
- Still insufficient
- Some available online: `https://ped.fz-juelich.de/da/doku.php`

Original Experiments at CTU

ID	Date	Num.	Video proc.	Note	Coorg.
E1	28/02/2012	86	manual	leaving room	MB
E2	10/12/2012	80	automatic (unreliable)	passing through	MB
E3	13/05/2013	80	automatic detection		MB
E4	29/04/2014	76	automatic identification		MB
E5	07/03/2016	54	semiautomatic	merging streams	MB
E6	20/12/2016	53	semiautomatic		MB
T2	00/06/2018	91	semiautomatic	train	HN
H1	05/06/2023	??	planned	leaving room	HN

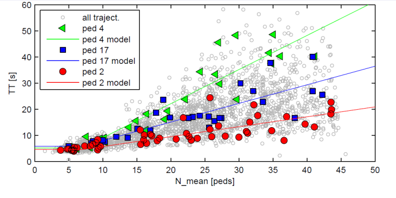
MB – Marek Bukáček (FNSPE), HN – Hana Najmanová (FCE)

Future plans

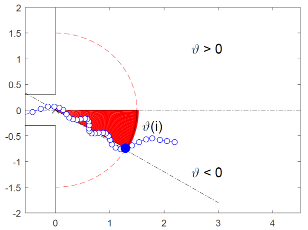
- Series of experiments focusing on heterogeneity planned in 2023-2026.
- Automatic data extraction in cooperation with ImproLab (FIT).
- Machine-learning methods for detecting heterogeneous behaviour.

E4 passing through – measured quantities

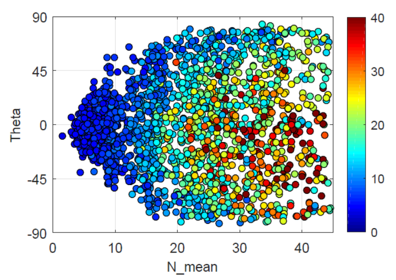
Travel time (TT)



Exit angle

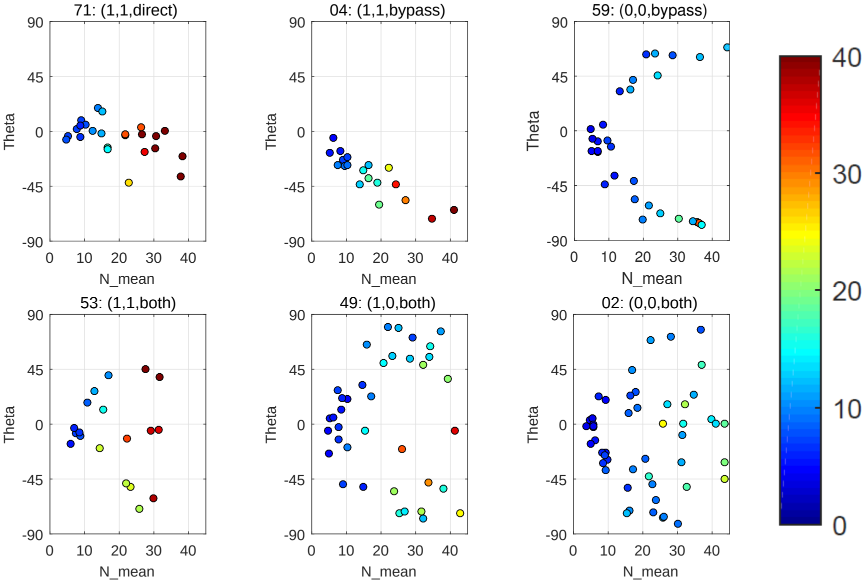


N-angle-TT diagram

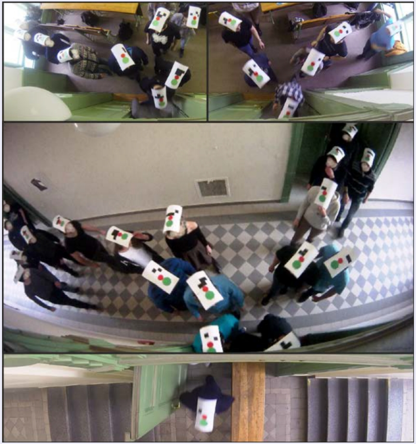


- Hats with ID enabled analysis of trajectories related to individual pedestrians.
- Internal heterogeneity revealed.

E4 passing through – strategies



E5+E6 merging streams

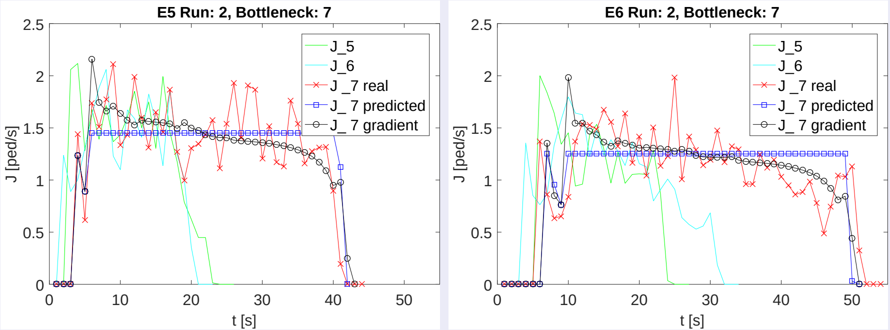


- Used for calibration of simple mass-transport process

$$
\begin{aligned}
J_i(t) &= \min(m_i(t), J_i^c) \\
m_i(t+1) &= m_i(t) - J_i(t) + \\
&\quad + \sum_{j \mid \exists e_{ji}} J_j(t - t_{ij})
\end{aligned}
$$

- Simultaneous experiment at AGH Kraków University of Technology

E5+E6 merging streams – flow decrease



- Flow decreasing in time despite clogging in front of the bottleneck.
- Possible explanation by loss of motivation.
- Heterogeneity offers alternative explanation.

Outline

Cellular automata modelling complex behaviour

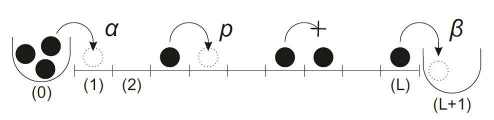
- Cell changing state according to states of neighbouring cells.
- Even simple rules can reproduce complex behaviour.
- Advantage: local interactions, computationally effective.

Conway's Game of Life (1970)

- Any live cell with fewer than two live neighbours dies, as if by underpopulation.
- Any live cell with two or three live neighbours lives on to the next generation.
- Any live cell with more than three live neighbours dies, as if by overpopulation.
- Any dead cell with exactly three live neighbours becomes a live cell, as if by reproduction.

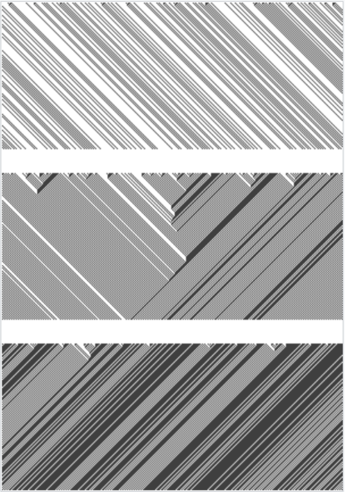
Hopping Particle Systems and Cellular Automata

TASEP (Derrida 1993)



- Probabilistic CA as traffic flow model
- Hopping particle random process
- Computer science meets statistical physics
- Cell state ↔ particle in lattice
- Simple rules lead to complex collective phenomena of 1D traffic flow

Rule 184 (Wolphram 1984)



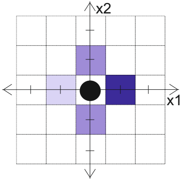
Floor-Field CA Model of Pedestrian Dynamics

Burstedde et al. Phys. A, 295(3-4):507-525, 2001.

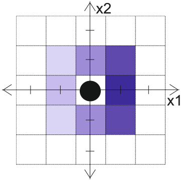
Probabilistic choice of target cell

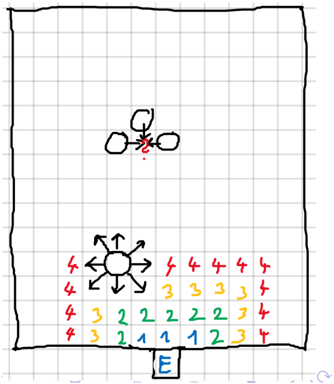
$$P(x \to y \,|\, N) \propto \exp\left\{ \sum_F k_F \cdot F(y) \right\}, \quad F(y) = \text{ field value for } y$$

von Neumann



Moore





- Navigation to exit given by attractiveness

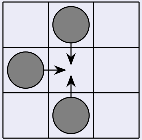
$$\exp\{-k_S S(y)\}$$

- $S(y) = \text{dist}(y, \text{exit})$

Floor-Field CA Model of Pedestrian Dynamics

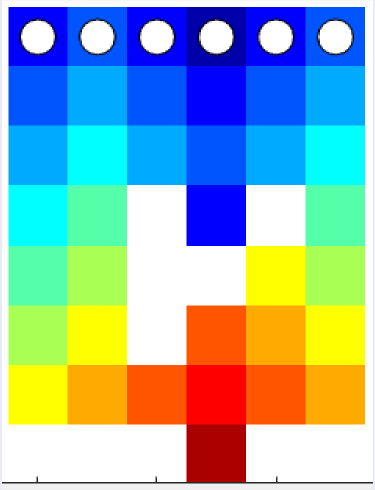
Floor-field conception

- Hard core repulsion = exclusion rule
- Parallel choice of target cell
- Conflicts appear



- Friction solution: no one wins with prob. μ.
- Otherwise one chosen randomly.

Cellular lattice



- Various extensions
- Some against advantage of CA
- Cells are limiting realism

Outline

Our Contribution to FF model

Acknowledged modifications

- 2012 Principle of bonds (line formation, compact crowd)
- 2013 Adaptive time span (heterogeneity in speed, diagonal movement)
- 2015 Aggressiveness (pushing through the crowd)
- 2017 Heterogeneity in aggressiveness and k_O (strategies)
- 2019 Spatially dependent friction (door width)
- 2023 Heterogeneity explaining flow decrease

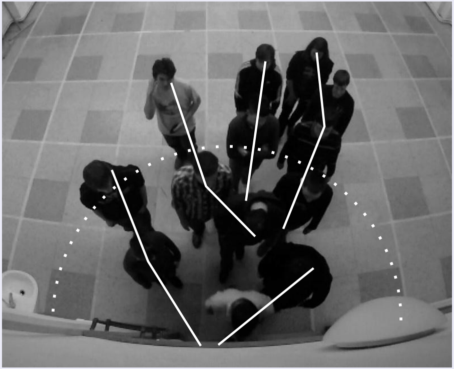
- Keeping the advantage of CA
- Leaning over conducted experiments
- Focus on introduction of heterogeneity

Collaborators and contribution

Marek Bukáček (bonds, time-span, aggressiveness, strategies).
František Gašpar (spatially dependent friction).
Matej Šutý (target choice as probability mixture)
Hotlib Mykola (flow decrease)

Principle of Bonds

Spontaneous line formation observed in experiments



- The goal was to capture the motion in lines on microscopic bases.
- Floor-field models excluded occupied cells from targets.
- No lines formed.

Principle of Bonds

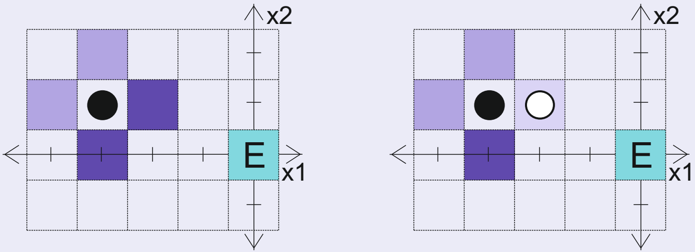
Target cell choice, original (2013)

$$\Pr(x \to y) \propto \exp\{-k_S \cdot S(y)\}(1 - k_O \cdot O_x(y))(1 - k_D \cdot D_{xy})$$

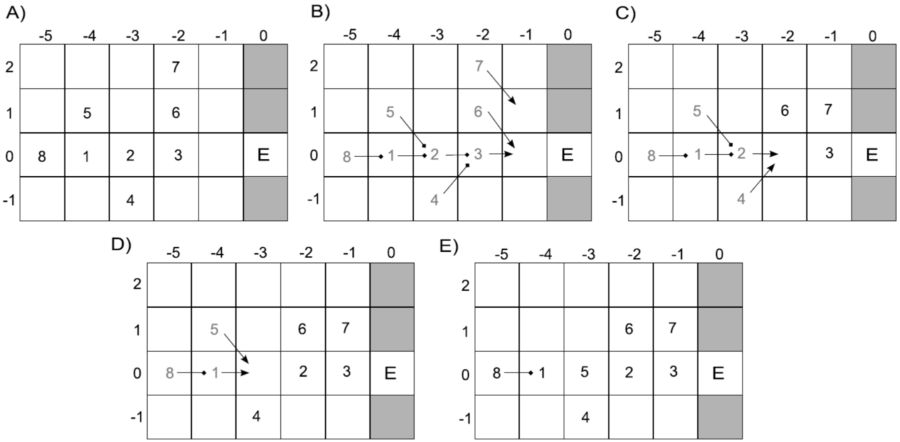
- Sensitivity to occupation $k_O \in [0, 1]$,

$$O_x(y) = \begin{cases} 1 & y \neq x \wedge y \text{ occupied}, \\ 0 & y = x \vee y \text{ empty}. \end{cases}$$

- Sensitivity to potential $k_S \in [0, +\infty)$.
- Diagonal motion penalization $k_D \in [0, 1]$.



Principle of Bonds

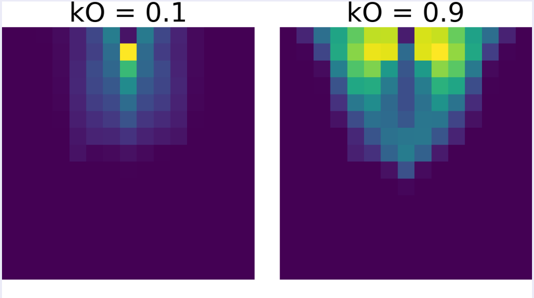


Principle of Bonds - Heterogeneity

Target cell choice as distribution mixture (2021-23)

$$\Pr(x \to y) = (1 - k_O)P_S(x \to y) + k_O P_O(x \to y)$$

Heterogeneity in k_O leads to different path-choice strategies



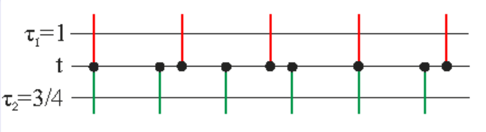
Adaptive time span

Usual Updating scheme

- Parallel
- Ordered Sequential
- Random sequential
- Random shuffled

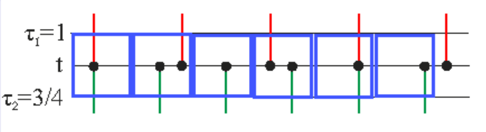
Adaptive time span (2013) – heterogeneity in velocity

- Event driven update
- Own updating period τ_i
- Adapts to diagonal movement
- Adapts to bonds



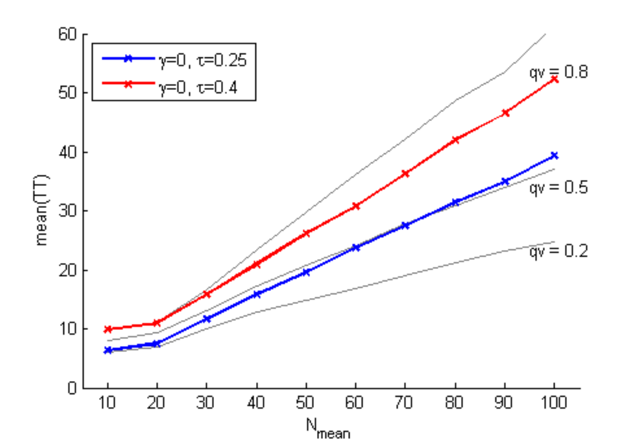
Partial synchronization (2014) – conflicts important

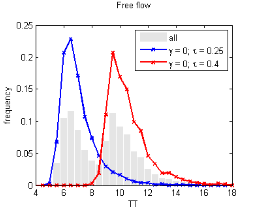
- Isochronous time interval
- Synchronous update of agents with activation time within interval

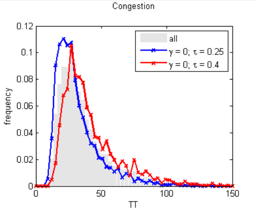


Adaptive time span

$\tau_1 = .4, \; \tau_2 = .25$





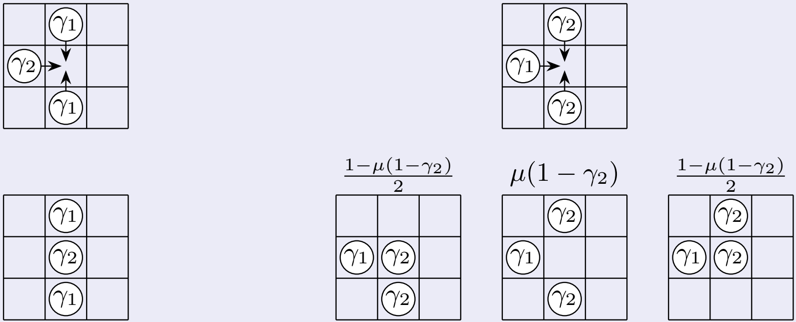


- Effect of heterogeneous velocity vanishes in crowd.
- Yet significant variance in motion in crowd experimentally observed.

Aggressiveness

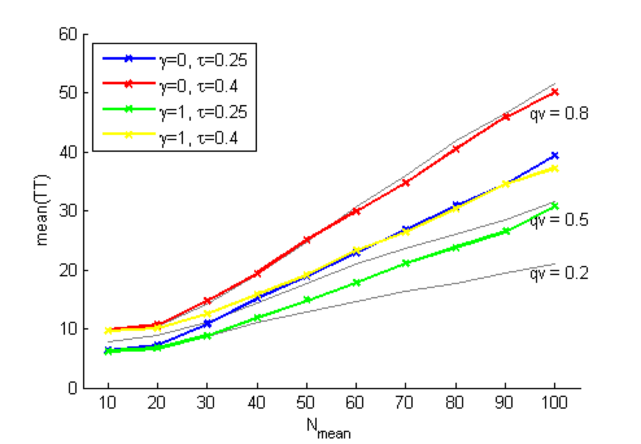
- "Aggressiveness" $\gamma \in [0, 1]$ represents the ability to win conflict.
- Conflict is won by the agents with higher γ.
- Friction μ plays role only when aggressiveness equals.
- Dedicated property of the agent.

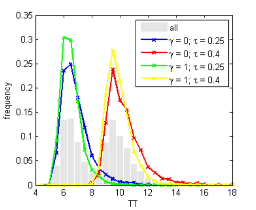
Heterogeneity in ability to win conflicts

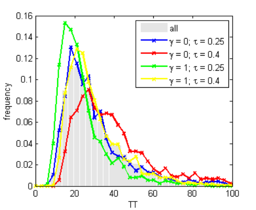


Aggressiveness

$\tau_1 = .4,\ \tau_2 = .25,\ \gamma_1 = 0,\ \gamma_2 = 1$



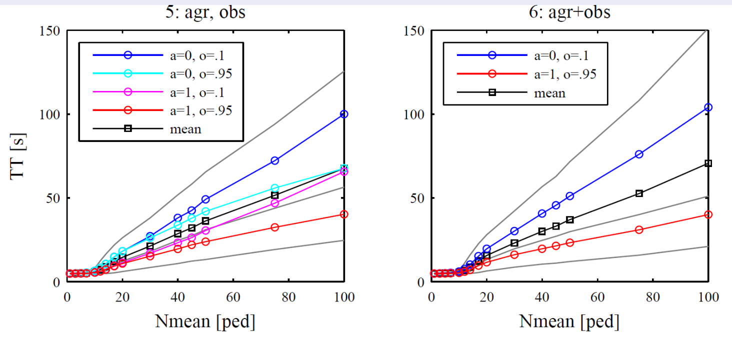




- Significant variance in congested crowd.
- Note: bonds principle still on $\Longrightarrow$ increases number of conflicts.

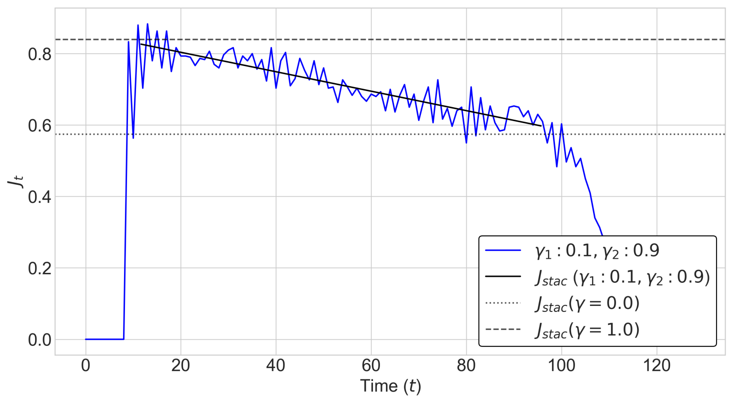
Heterogeneity and Strategies

- Occupation sensitivity k_O affects the willingness to bypass the crowd or join the line.
- Aggressiveness γ affects the ability to win conflicts.
- Observed strategies can be revealed.



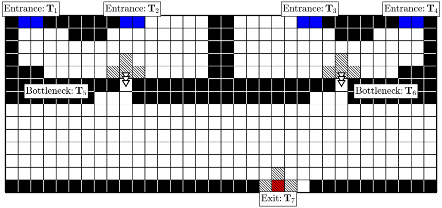
Heterogeneity Explains Decrease of Flow

Simulated flow in Leave-the-room scenario



- More aggressive leaving earlier, less aggressive staying longer.
- May explain the observed decrease of flow.

Spatially dependent friction

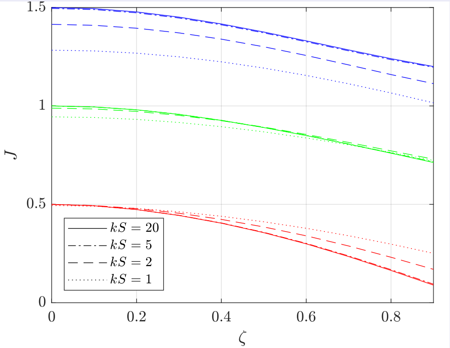


- Measured/estimated maximal flow through given bottleneck
- Local friction according to **model** friction-flow dependence
- How to find the dependence

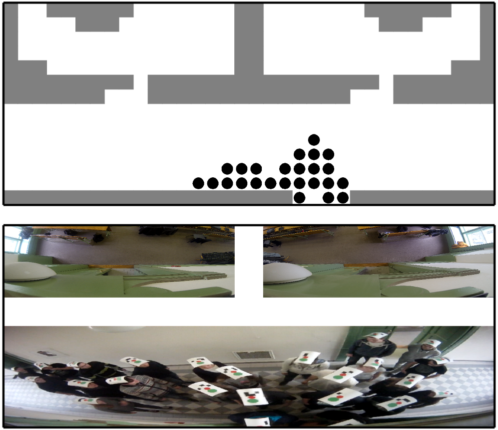
$$J = J(\zeta; k_S, \text{parameters})?$$

Friction-flow dependence

$$J = J(\zeta; k_S, \dots)$$



Spatially dependent friction



Outline

Train Evacuation