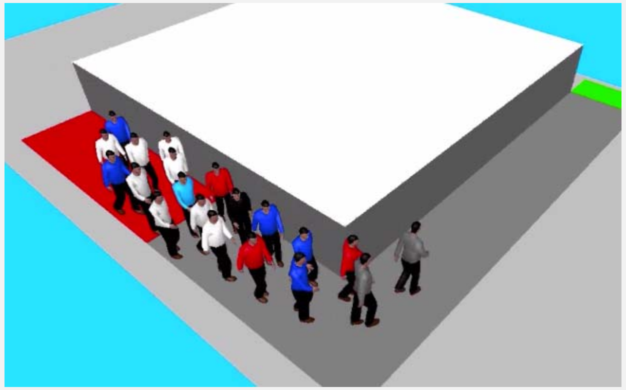
Crowd Management and Control: Preventing Crowd Disasters During the Hajj



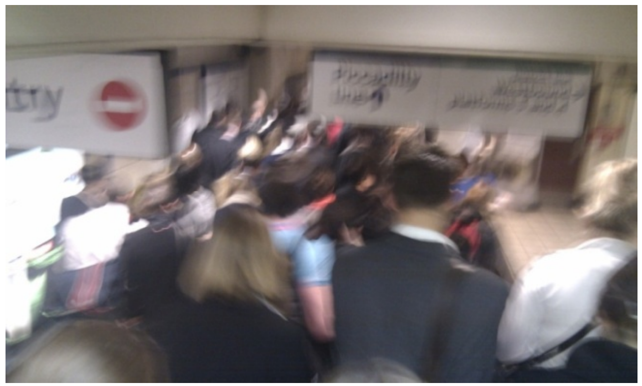
Anders Johansson

www.ajohansson.com

Crowd research motivation

As the planet gets increasingly crowded, rather than utilizing all the available space, there is a trend of people to cluster even denser in cities, and at other locations during mass gatherings

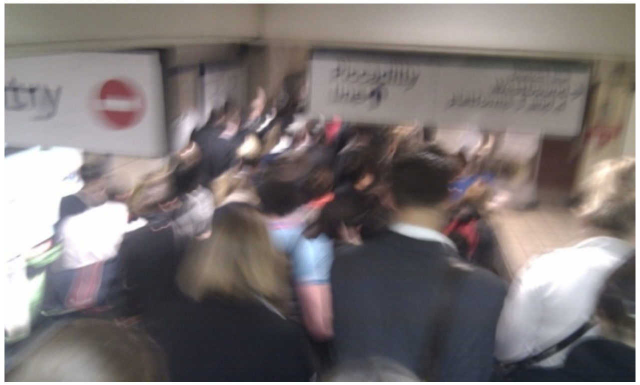
These two effects put together lead to some particularly over-crowded locations, scattered around the planet



Crowd research motivation

No doubt, there are many positive effects of bringing people together

However, there are also several negative outcomes when the density of people grows too high, such as increased **crime**, severe **traffic delays**, and **pollution**. Densely populated areas are also ideal media for **epidemics** to spread in, due to the proximity of people and their frequent interactions



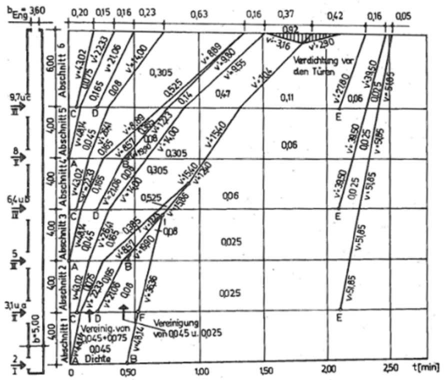
Crowd research – The ‘observation era’ 1890—1979

Gustave Le Bon (1896): Studied crowds with a focus on crowd psychology and herding

Wsewolod Predtetschenski and Anatoli Milinski (1971): Used soldiers for crowd experiments, manually collected data, and came up with analytical formulas

John Fruin and Jake Pauls (1970s): Used video cameras to analyze walking

Le Bon (Delacroix)



Predtetschenski & Milinski

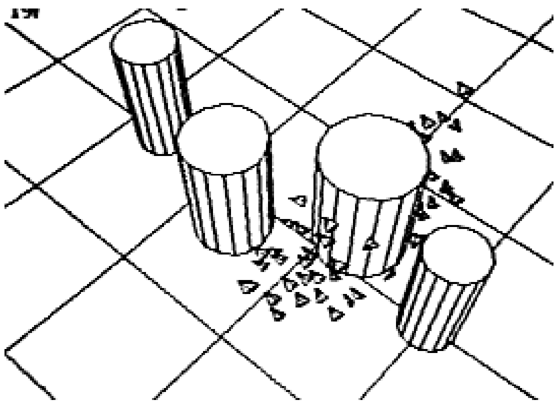
Fruin & Pauls

Crowd research – The ‘simulation era’ 1980—2006

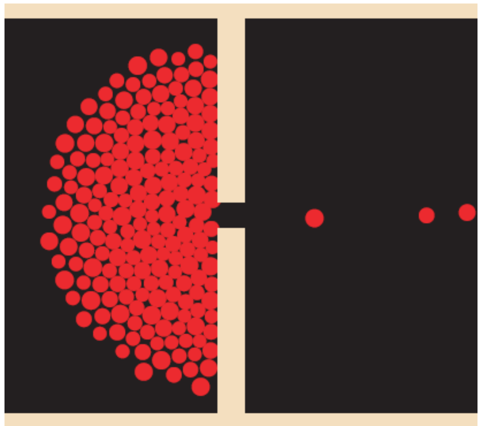
Reynolds (1987): ‘Boids model’ – a swarm-inspired model of interacting individuals

Helbing et al. (2000): ‘Social-force model’ – a particle-physics-based model of crowd panic

Treuille et al. (2006): ‘Continuum crowds’ – a fluid-dynamic model of emergent crowd phenomena



Reynolds



Helbing et al.

Treuille et al.

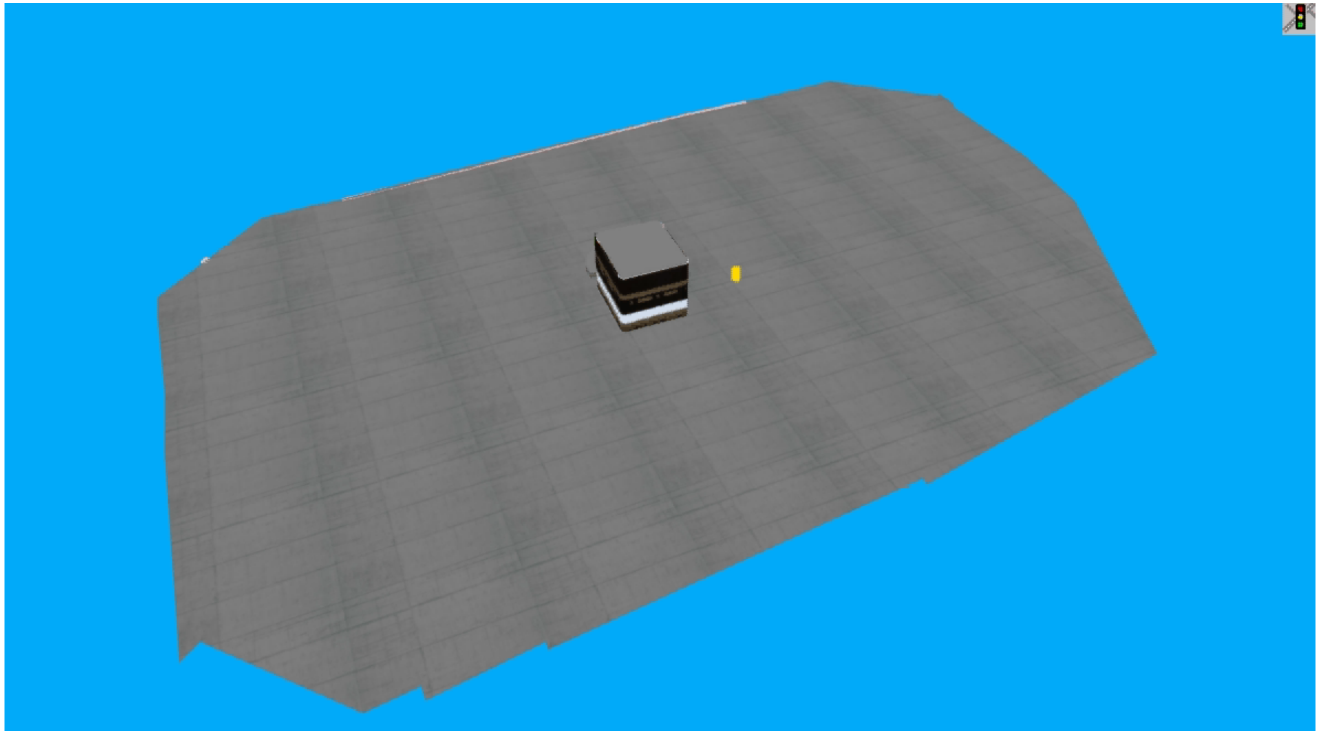
Crowd research – The 'prediction era' 2007—2010

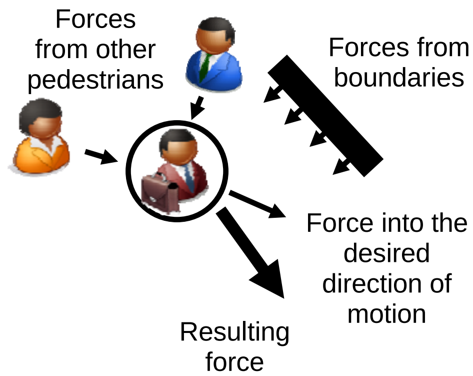
Today's modern tools include:

Crowd simulation (Planning phase)

$$\vec{f}_\alpha(t) = \frac{1}{\tau_\alpha}(v_\alpha^0 \vec{e}_\alpha - \vec{v}_\alpha) + \sum_{\beta(\neq\alpha)} \vec{f}_{\alpha\beta}(t) + \sum_i \vec{f}_{\alpha i}(t)$$

$$\frac{d\vec{v}_\alpha(t)}{dt} = \vec{f}_\alpha(t) + \vec{\xi}_\alpha(t)$$



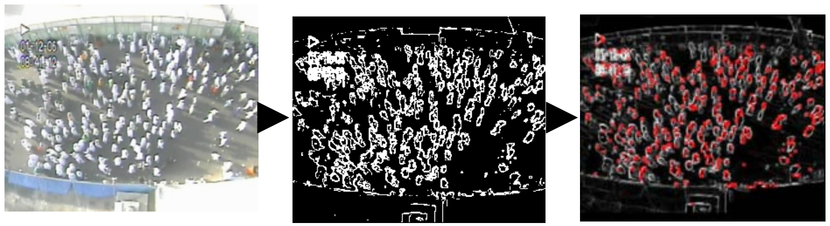


Johansson and Helbing. Together with PTV AG.

Crowd research – The ‘predictive era’ 2000—2010

Today’s modern tools include:

Automated video analytics (Live, during event)



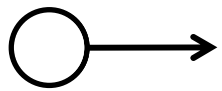
Johansson, 2009b
Helbing, Johansson, Al-Abideen, 2007

Winner - 2008
GLOBAL SECURITY CHALLENGE
Crowded Places Idea

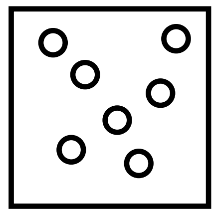
Pedestrian-flow theory

Pedestrian-flow theory is mainly based on the following quantities:

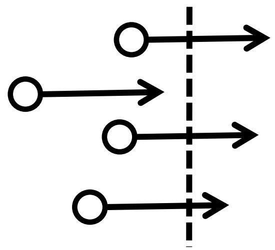
Velocity (meters / second)



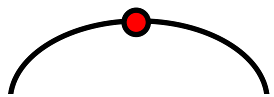
Density (people / m^2)



(Specific) flow = Velocity x Density (people / meter / second)



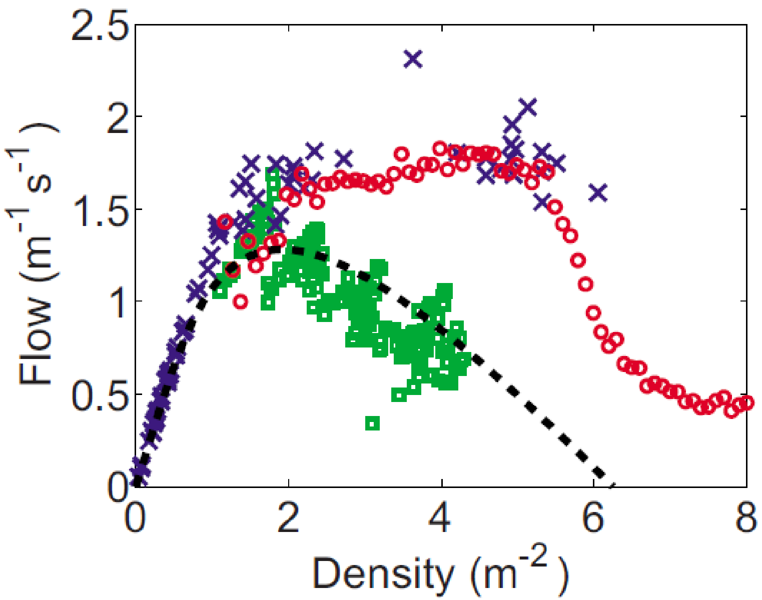
Capacity = The maximum possible flow



Pedestrian-flow theory (II)

Pedestrian-flow theory is based on the relation of the pedestrian flow (people/meter/second) as a function of the pedestrian density (people/m^2).

The fundamental diagrams look different in different studies

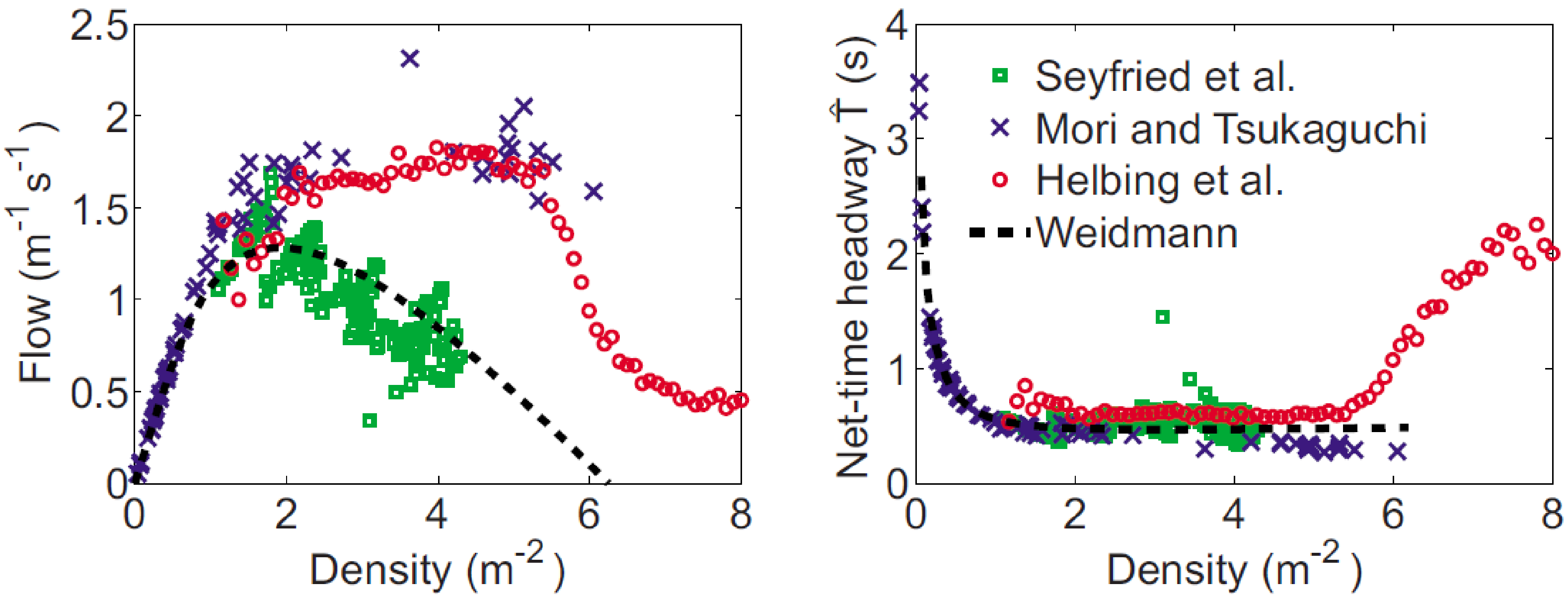


Pedestrian-flow theory (II)

The fundamental diagrams look different in different studies

However, if one look at the relation of the net-time headway as a function of density however, it always settles at a constant value around 0.5 s

$$\hat{T} = \hat{d}/v = \left(1/\sqrt{\rho} - 1/\sqrt{\rho_{max}}\right)/v$$



Johansson, 2009a

Self-organization

Pedestrian dynamics can be understood as a combination of two different levels:

Planning level: Route choice and navigation on a larger scale

Operational level: Navigating on a smaller scale, e.g. Avoiding collisions with fellow pedestrians and obstacles

From simple pair-wise interactions between pedestrians, various patterns emerge on a macroscopic scale – this is called **self-organization**

Examples include:

Land formation, oscillations at bottlenecks, intermittency, stop-and-go waves, crowd turbulence

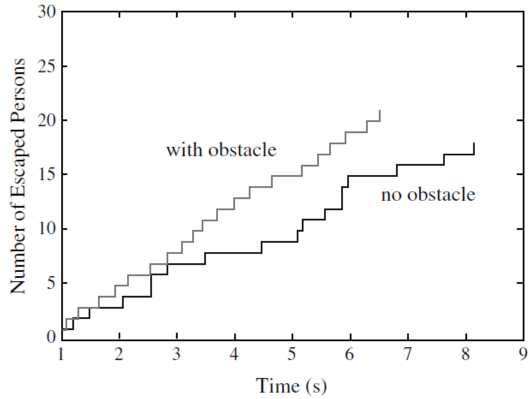
Self-organization – Lane formation

Pedestrians self-organize into lanes as a result of pair-wise repulsive forces:

Helbing, Buzna, Johansson, Werner, 2005

Self-organization – Intermittency

Uni-directional pedestrian flow through a narrow bottleneck is not smooth, but rather intermittent, with periods of total blockages and bursts of outflow of small groups of people



Helbing, Buzna, Johansson, Werner, 2005

Large crowds – The Hajj

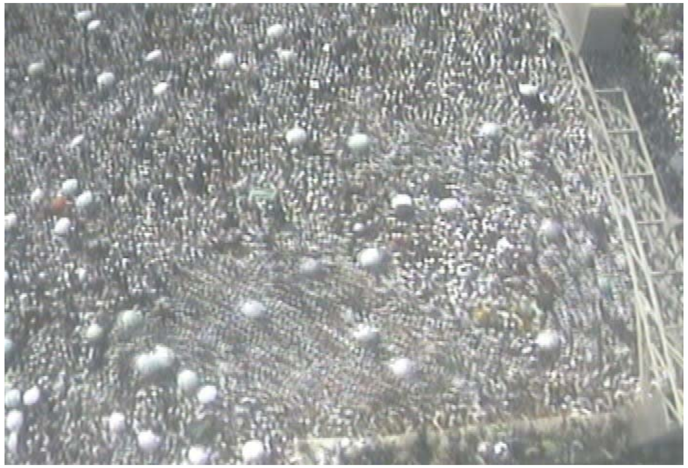
What happens with the crowd when it gets so large and dense that individual pedestrians can no longer keep a global overview of the situation?

Stop-and-go waves and 'crowd turbulence'

In 2006, there was a crowd disaster, where 363 pilgrims lost their lives. Since CCTV footage exists, it was possible to scientifically analyze the crowd disaster.

When the crowd density was increasing, two sudden transitions were found: from smooth (laminar) flow to stop-and-go-flow, and further to crowd turbulence.

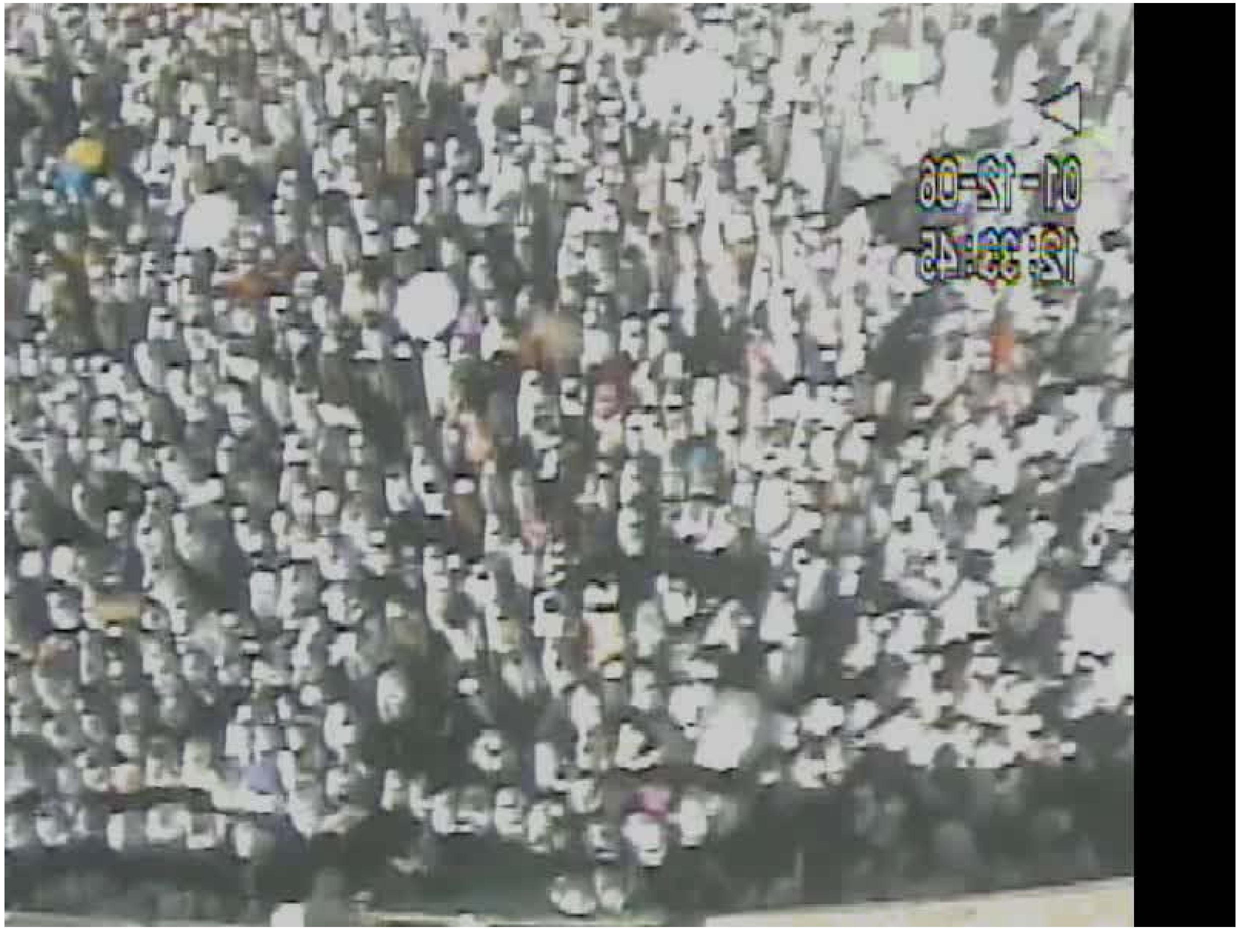
Stop-and-go flow



Crowd turbulence

Stop-and-go waves

When the crowd density is high enough, smooth uni-directional flow breaks down into dynamic stop-and-go waves

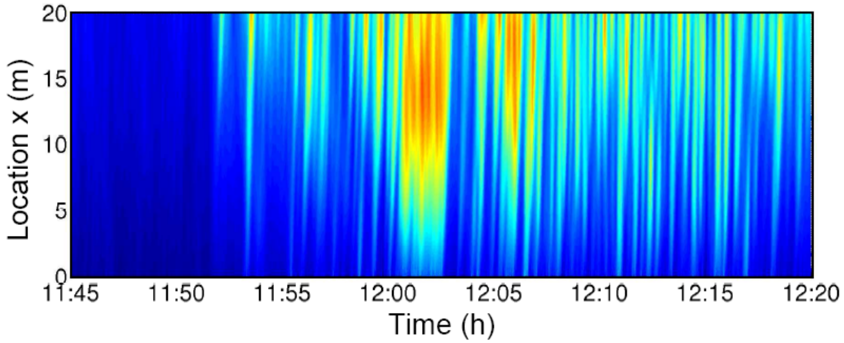


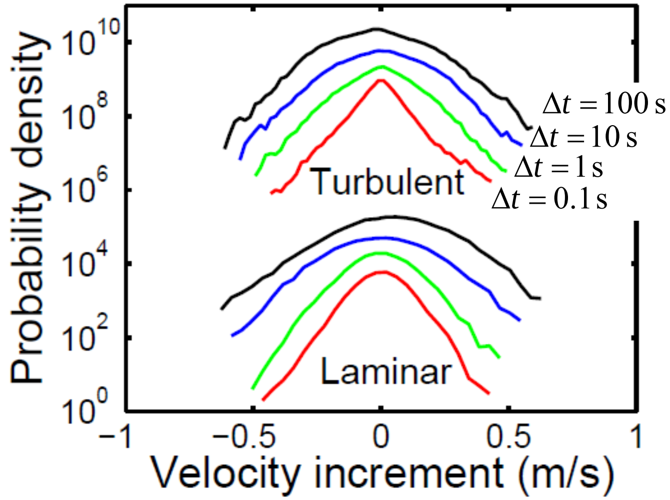
‘Crowd turbulence’

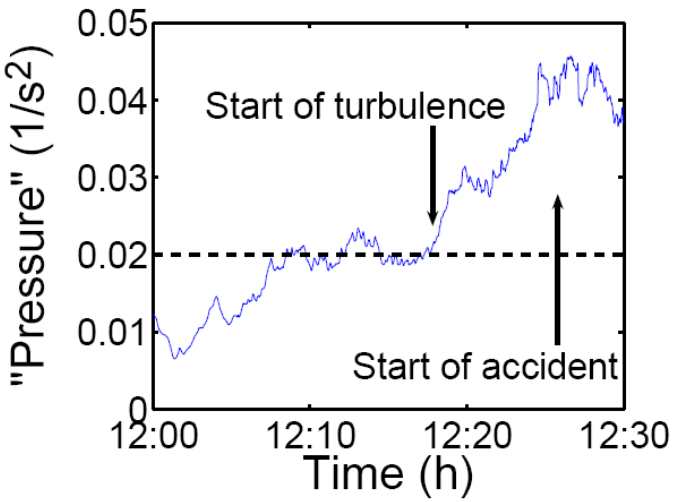
For even higher crowd densities, pedestrians are involuntarily moved around by the crowd in an unpredictable way

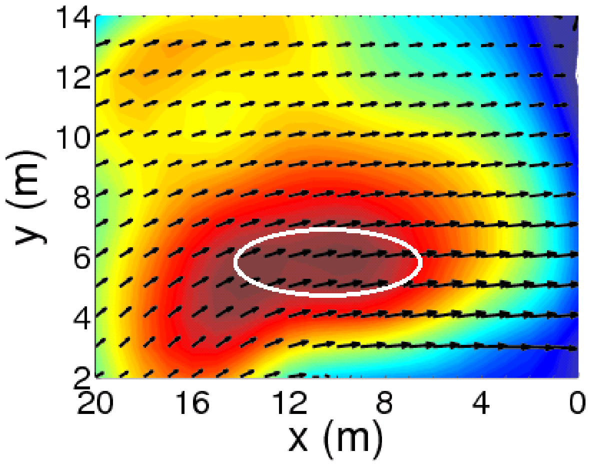
Towards forecasting of crowd disasters

Density as function of time and space. One can clearly see the emerging stop-and-go waves









Gas-kinetic pressure

$$P(t) = \rho(t)\mathrm{Var}_t(\vec{V})$$

as a function of

(a) time, and

(b) space

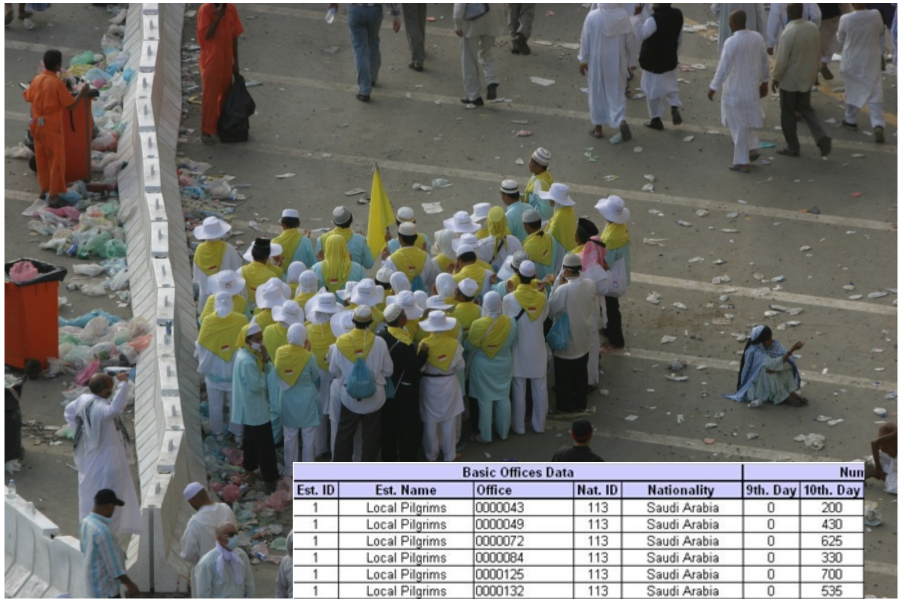
Helbing, Johansson, Al-Abideen, 2007

Generality of crowd patterns – Love Parade 2010, Germany

Re-engineering the Hajj

Various measures have now been implemented, and the crowds are now much better organized

One-way, balanced, street system



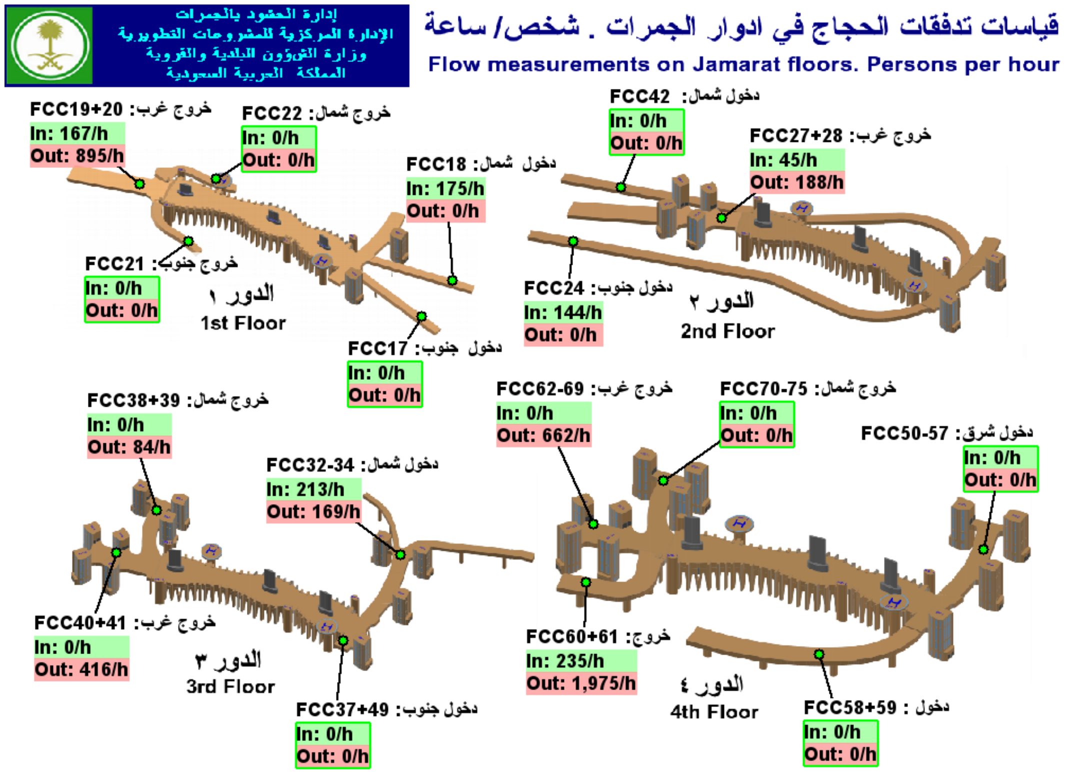
Basic Offices Data					Num	
Est. ID	Est. Name	Office	Nat. ID	Nationality	9th. Day	10th. Day
1	Local Pilgrims	0000043	113	Saudi Arabia	0	200
1	Local Pilgrims	0000049	113	Saudi Arabia	0	430
1	Local Pilgrims	0000072	113	Saudi Arabia	0	625
1	Local Pilgrims	0000084	113	Saudi Arabia	0	330
1	Local Pilgrims	0000125	113	Saudi Arabia	0	700
1	Local Pilgrims	0000132	113	Saudi Arabia	0	535
1	Local Pilgrims	0000144	113	Saudi Arabia	0	270

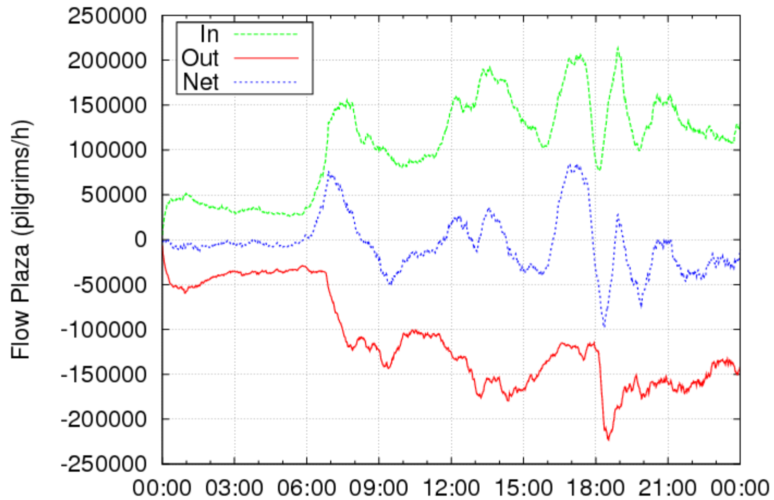
A large portion of the pilgrims belong to a group and have a schedule assigned to them

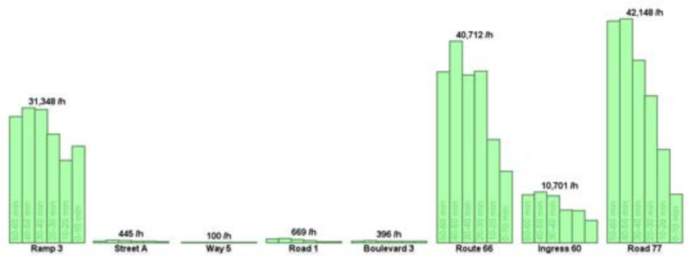
With Haase, Al-Abideen, Al-Bosta

Re-engineering the Hajj – Real-time crowd analytics system

Since 2007, there is a system in place, that analyze live feeds coming from CCTV, from almost 100 cameras around the Jamarat Bridge – results are presented in **real time**

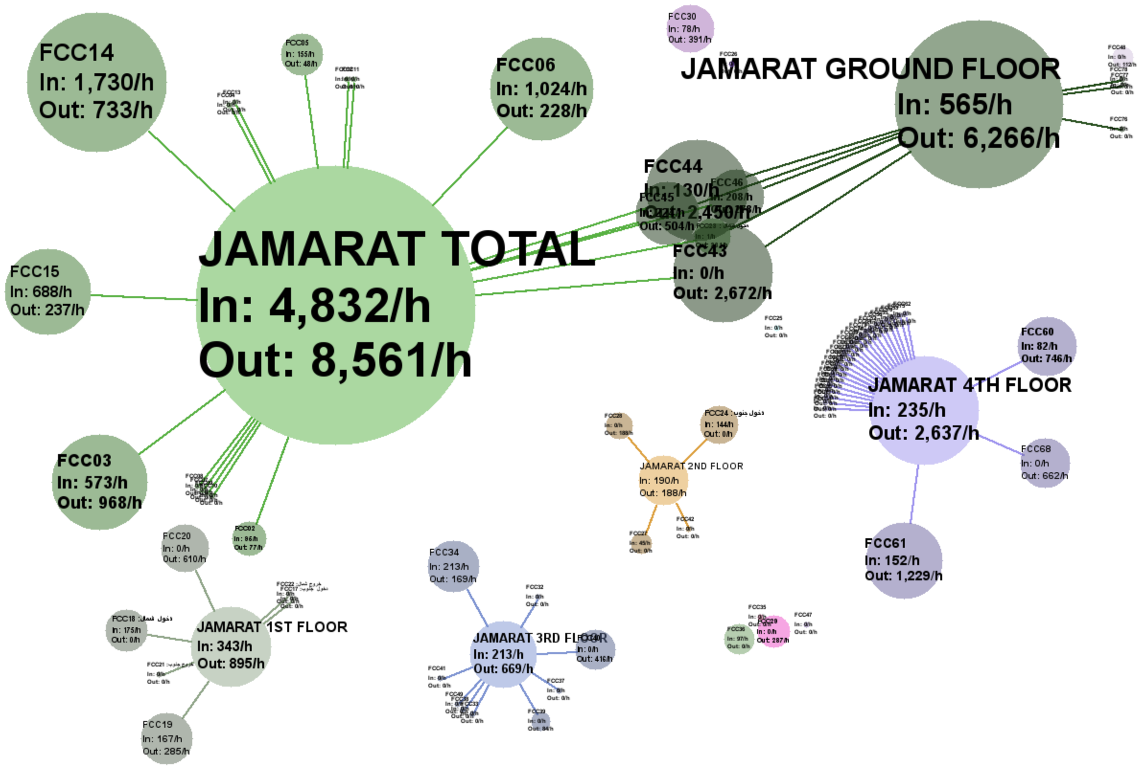


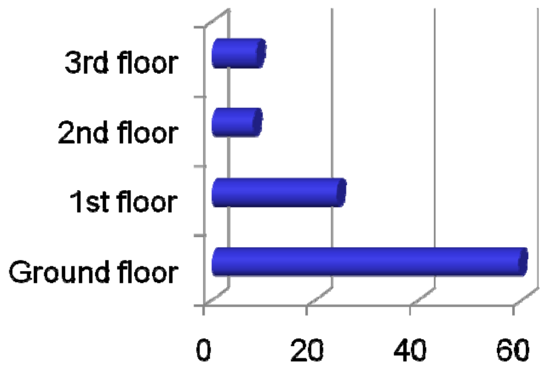




Re-engineering the Hajj – Real-time crowd analytics system

Since 2007, there is a system in place, that analyze live feeds coming from CCTV, from almost 100 cameras around the Jamarat Bridge – results are presented in **real time**





Re-engineering the Hajj

Also vehicular traffic is of particular concern. There is a shift from small personal cars to busses and a new metro

Situation before

Shuttle bus and metro

Did all these changes have an impact?

Hijjah	Year	Day	Time	Location	Number dead	Number injured
1414	1994	12	01:25	Al- North of Jamarah Soughra	266	98
1415	1995			No major accidents		
1416	1996			No major accidents		
1417	1997	12	15:10	North Side of the Eastern Entrance	22	43
1418	1998	12	13:30	North Side of the Eastern Entrance	118	434
1419	1999			No major accidents		
1420	2000			No major accidents		
1421	2001	10	08:12	Al-Kubra North of Jamarah	35	179
1422	2002			No major accidents		
1423	2003			No major accidents		
1424	2004	10	08:54	Al-Kubra North of Jamarah	249	252
1425	2005			No major Accidents		
1426	2006	12	13:30	North Side of the Eastern Entrance	363	289
1427	2006/7			No major Accidents		
1428	2007			No major Accidents		
1429	2008			No Major Accidents		
1430	2009			No Major Accidents		

Major changes in Jamarat area →

Source: www.crowddynamics.com

Crowding in cities

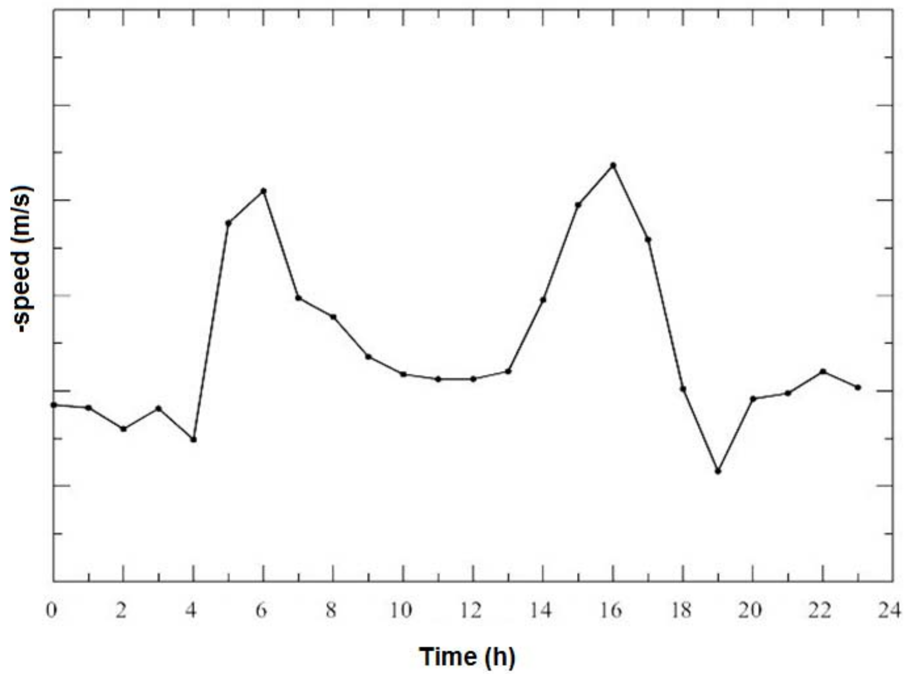
- Is all this relevant also for everyday life in cities?
- People are not routinely dying of overcrowding (yet!)
- However, there are several shared properties and characteristics that are found in different kinds of crowds

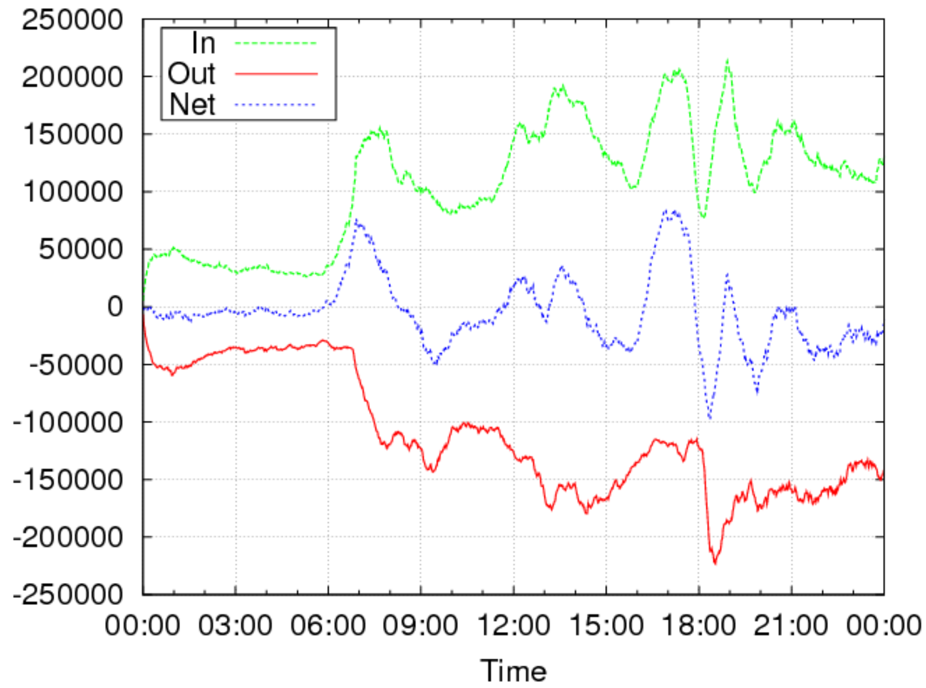
Mecca

London

Exogenous forces

Most crowded places are driven by exogenous forces





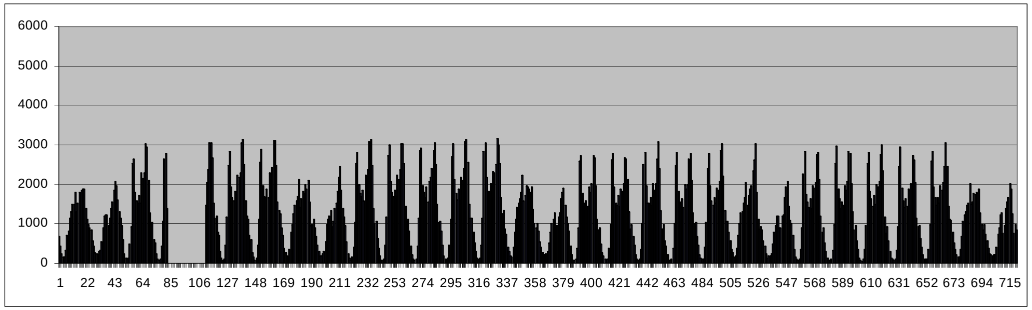
Torino: Peaks correspond to commuting (from: Bazzani)

Mecca: Peaks correspond to praying times

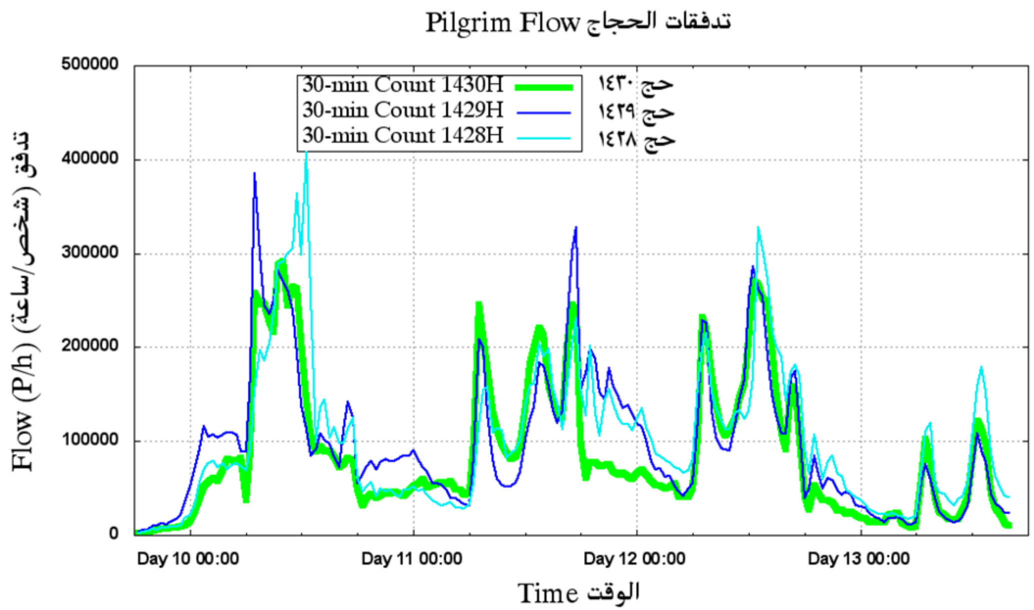
Repeating patterns

Even the most chaotic system often exhibits repeating patterns

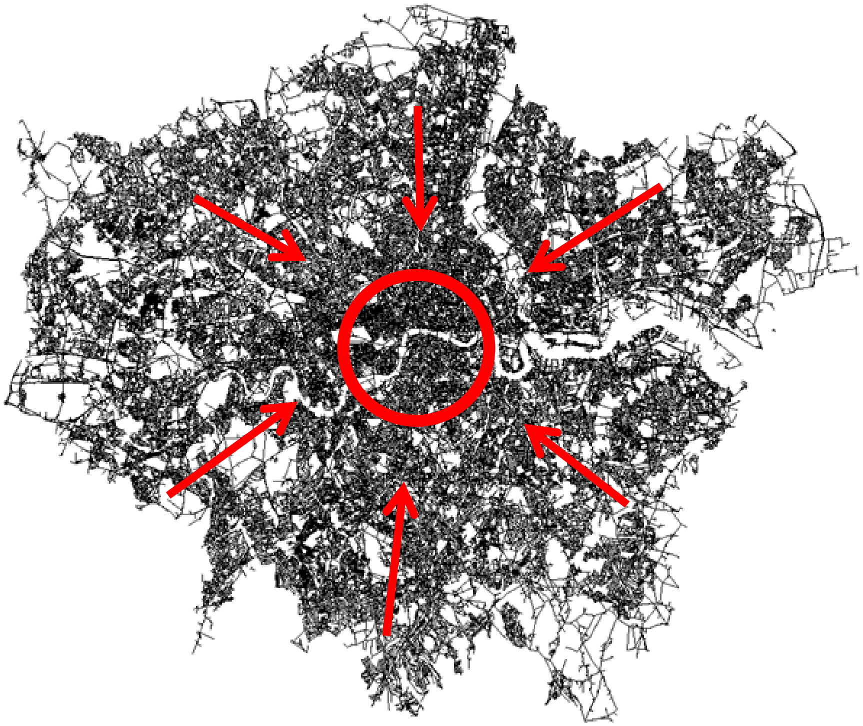
Torino: Daily flow of people tend to repeat itself from day to day (from: Bazzani)



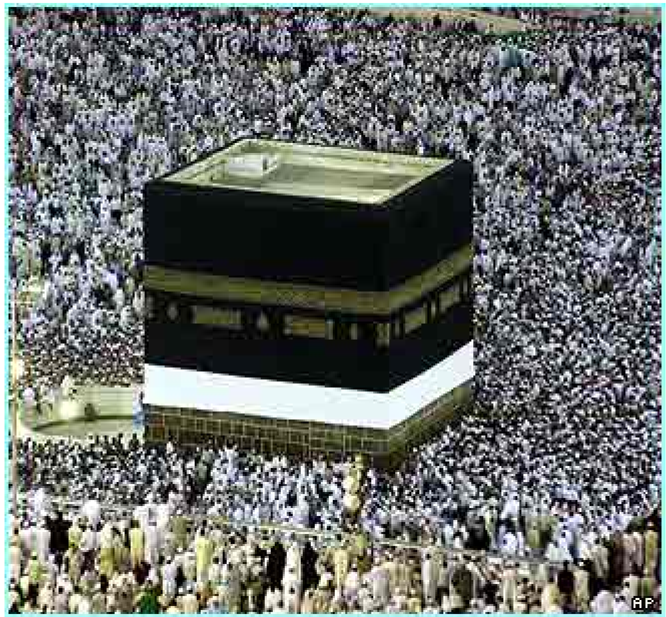
Mecca: Pilgrim flow data from three different years show a high degree of overlap



Movement towards a focal point



London: Movement directed towards the city centre



Mecca: Pilgrim flow directed towards the Kaaba

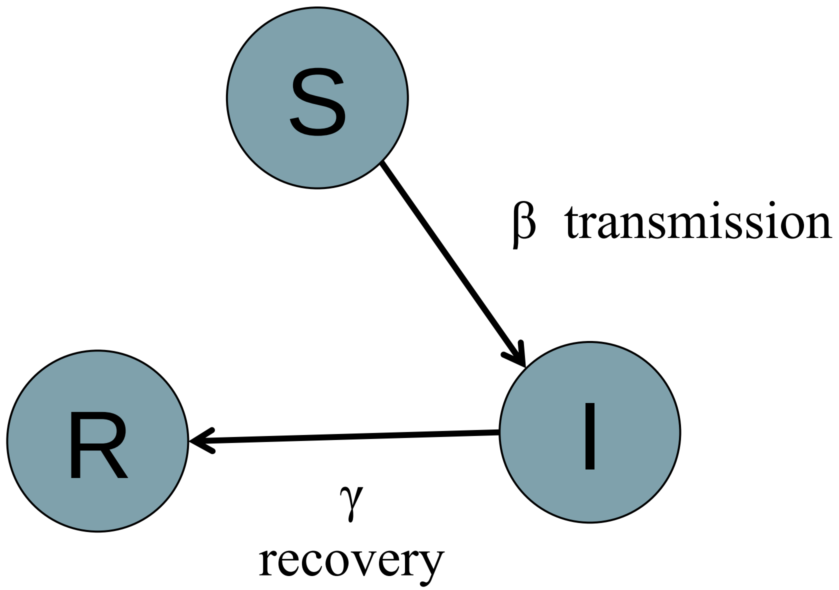
Disease transmission

In crowded places, fear of over-crowding is not the only concern. Another area of concern is the spreading of diseases

Epidemics modeling

The Kermack-McKendrick model is specified as:

S: Susceptible persons
I: Infected persons
R: Removed (immune) persons
β: Infection rate
γ: Immunity rate



Epidemics modeling – Macroscopic approach

The Kermack-McKendrick model is specified as:

S: Susceptible persons
I: Infected persons
R: Removed (immune) persons
β: Infection rate
γ: Immunity rate

$$\frac{dS}{dt} = -\beta\, I(t)S(t)$$

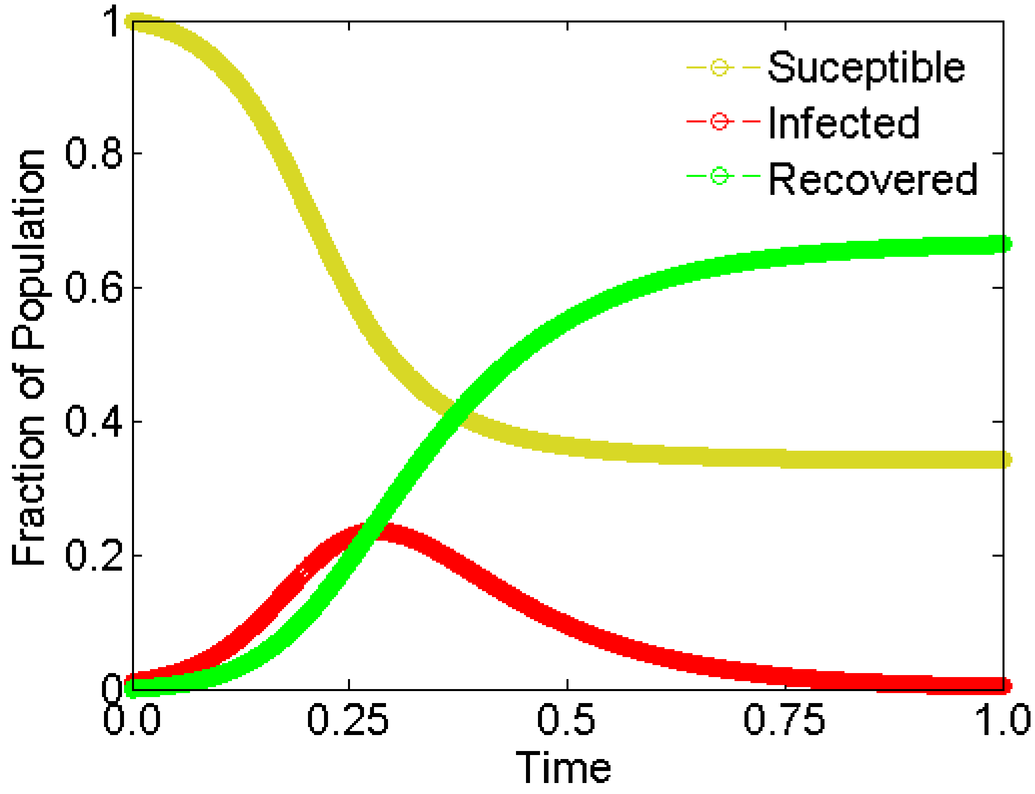
$$\frac{dI}{dt} = \beta\, I(t)S(t) - \gamma\, I(t)$$

$$\frac{dR}{dt} = \gamma\, I(t)$$

Epidemics modeling – Macroscopic approach

The Kermack-McKendrick model is specified as:

S: Susceptible persons
I: Infected persons
R: Removed (immune) persons
β: Infection rate
γ: Immunity rate

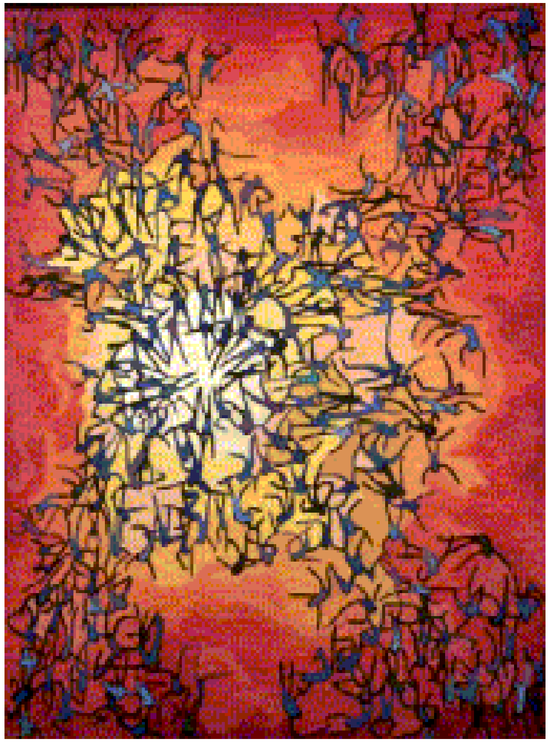


Epidemics modeling – Microscopic approach

Real populations are not in equilibrium and perfectly mixed and homogenous as is assumed by these differential equations

Therefore, it would be more attractive to run epidemics models on a microscopic, individual-based level

Viruses spreading in flight network (Colizza et al., 2006)

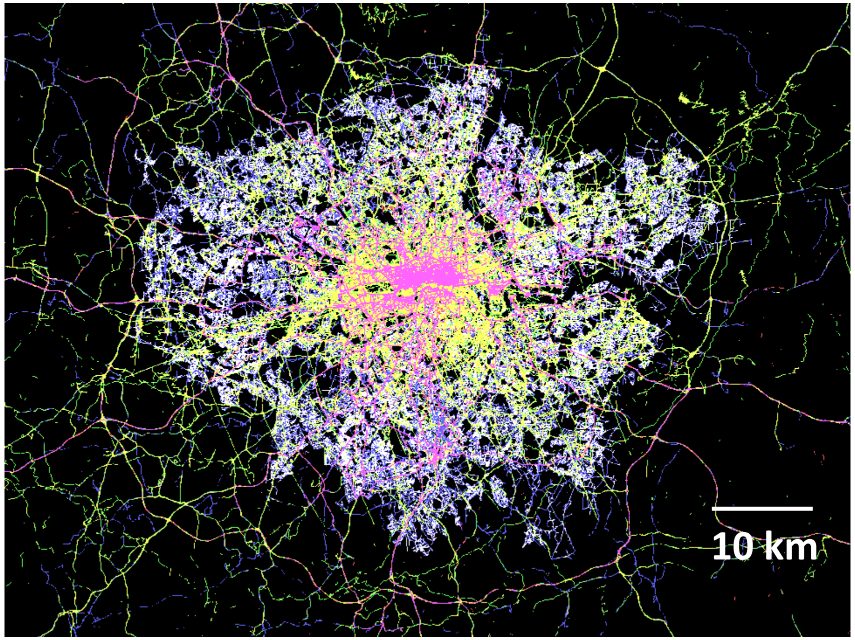


Viruses spreading in social networks (Liljeros et al., 2001)

Epidemics modeling – Microscopic approach

To really connect epidemics spreading to an individual level, let us use GPS trajectories of individuals moving around in central London, and assume that:

- initially 1% of the population is infected with a certain disease,
- they will pass this on to other people within a 10 m radius, with a probability β, and
- they will recover from the disease with a probability *γ*

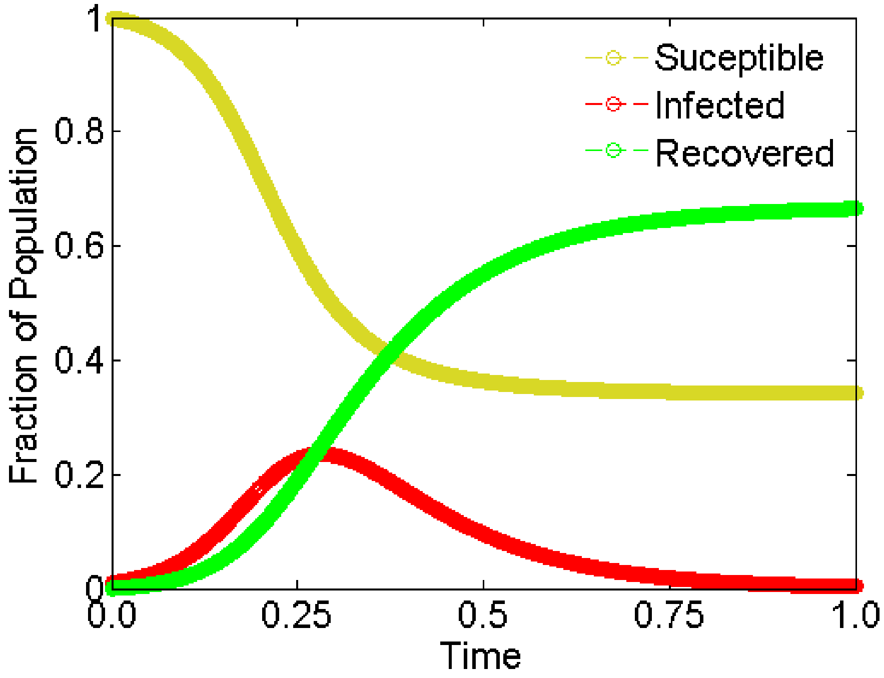


London trajectories

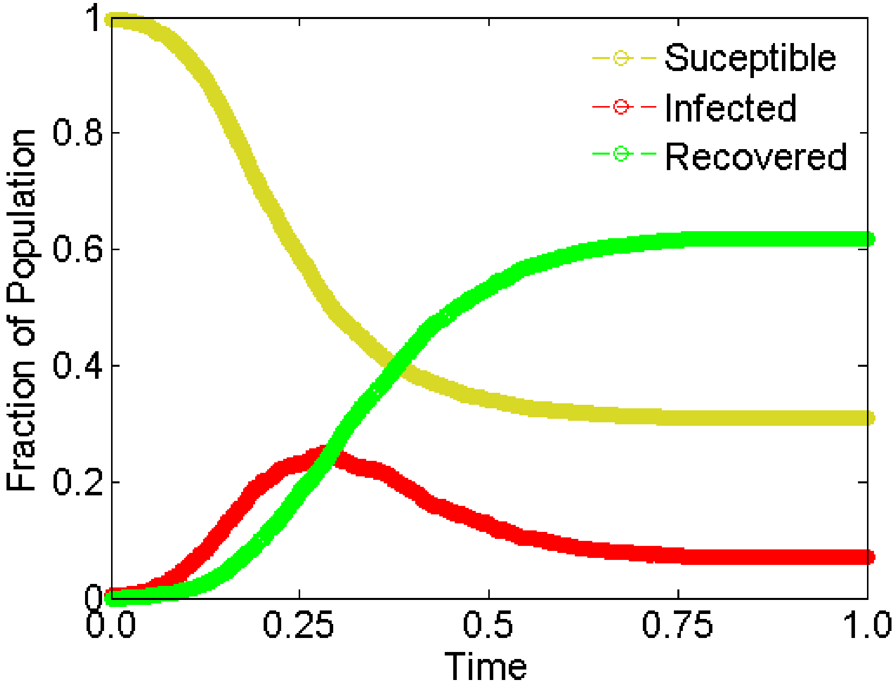
Video

Epidemics modeling – Macro vs micro approach

Let us compare the results of the micro and the macro approaches:



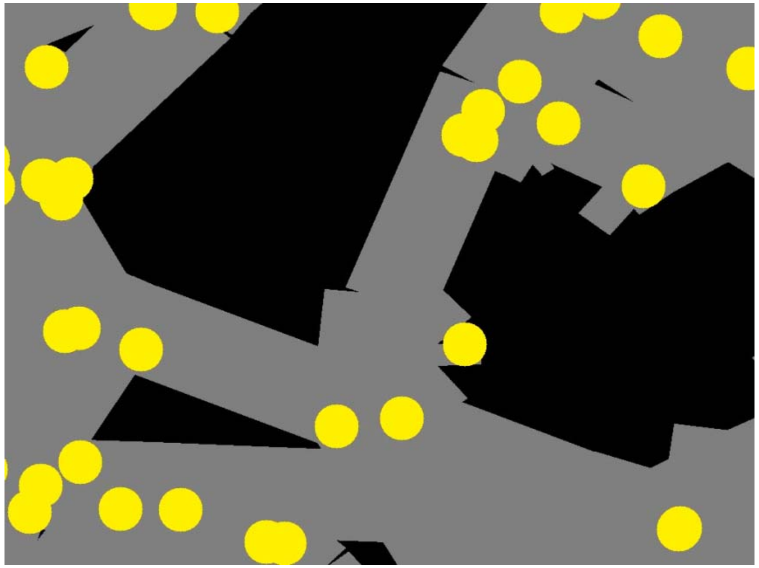
Macro approach



Micro approach

Epidemics modeling – Macro vs micro approach

- The advantage of a microscopic approach to epidemics modeling is that the interventions that one can make (immunize, quarantine, etc.) work on a *micro* level
- The disadvantage with using GPS trajectories is that there are obvious gaps in the data, but these gaps can be filled with microscopic *simulation*



Conclusions

- Do not try to control a system before you understand it

- Identify both the similarities and the dissimilarities of different events and systems

- Do not be satisfied with the state-of-the-art, but aim beyond it

Thank you for your attention!

For more information:

www.ajohansson.com

a.johansson@ucl.ac.uk

Collaborators:

ETH Zurich: Prof Dr Dirk Helbing

MoMRA, Riyadh: H E Dr Habib Al-Abideen, Dr Salim Al-Bosta

TU Dresden/CUHK: Sonic Chan, Prof Dr Knut Haase

UCL: Prof Dr Michael Batty

PTV AG, THALES, Crowd Vision Ltd, Ecourier