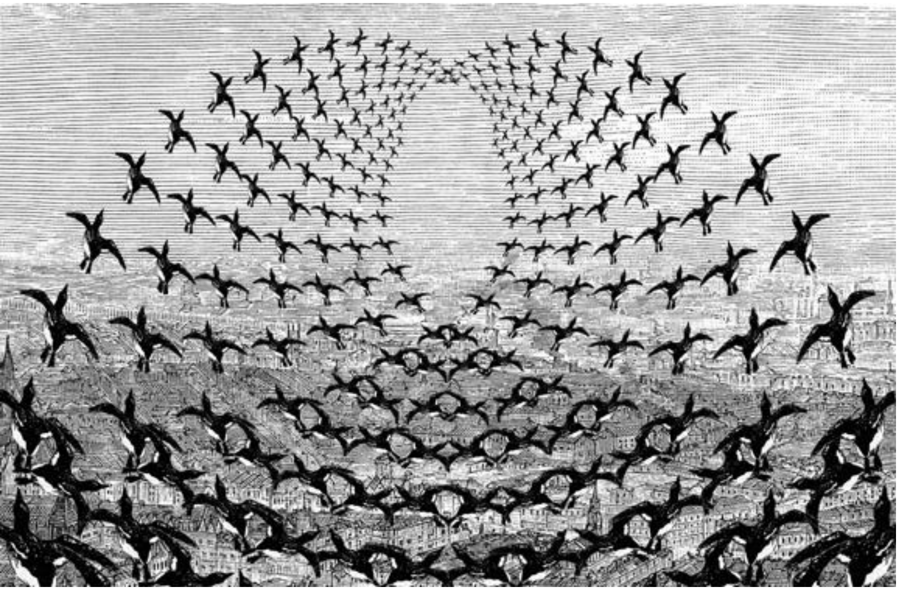
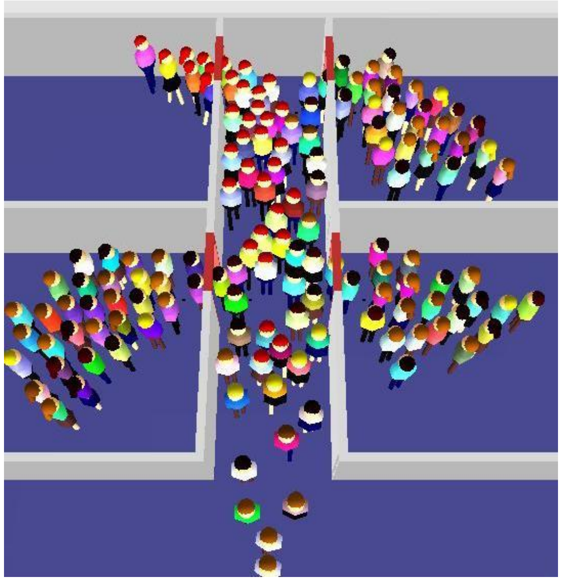
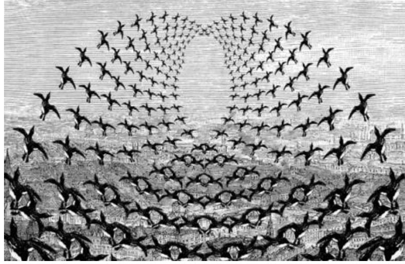
Crowd simulation





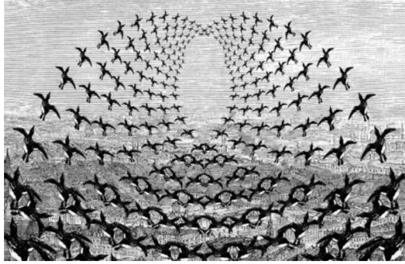
Taku Komura

Animating Crowds



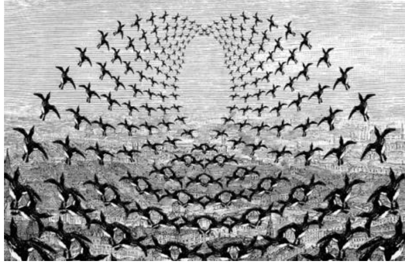
- We have been going through methods to simulate individual characters
- What if we want to simulate the movement of crowds?
  - Pedestrians in the streets
  - Flock of birds, school of fishes
  - People in panic

Why need a crowd simulation ?

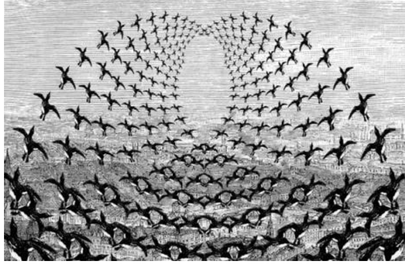


- Capturing scenes with many people
  - Expensive to hire many extra actors
  - We don’t see the details : use simple computer-based models
- Security reasons:
  - Need to evaluate the safety of buildings, environments
  - Important process of the design
- Automatic driving
  - Generating training data for the system

Overview



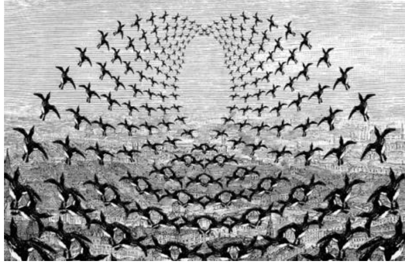
- Agent based Methods
  - Flocking
  - Intention generator
  - Creating scenes with human crowds
  - Patch-based methods
    - Create scenes by building blocks
  - (Local) Collision avoidance
    - Enhancing flocking to produce social behaviour
    - Velocity obstacle, reciprocal velocity obstacle
- Global methods
  - Flow-based approaches
  - Potential Field based approaches



Flocking Models – Most basic agent model (Reynolds ’87)

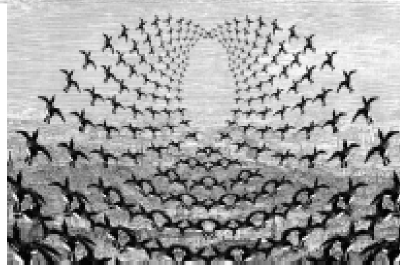
- The agents interact based on simple dynamics
- Good to simulate
  - Flock of birds flying,
  - School of fishes swimming

Forces applied to individuals



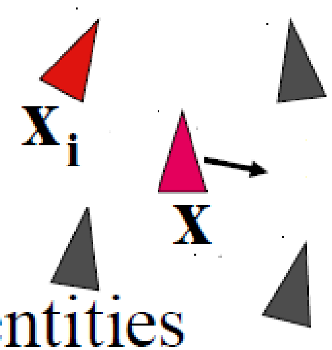
- Separation
- Alignment
- Cohesion
- Avoidance

Separation

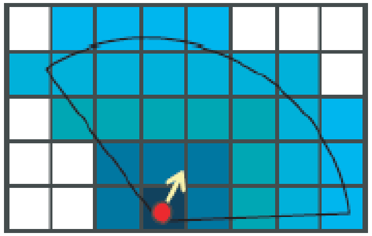


- Try to avoid running into local flock-mates
  - Use a *perception volume* to limit visible flock-mates

$$\mathbf{F_s} = \sum_{i \in S} \left(\frac{\mathbf{x} - \mathbf{x_i}}{\left\| \mathbf{x} - \mathbf{x_i} \right\|^2} \right)$$

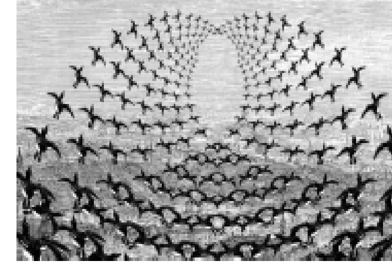


  - S : surrounding entities

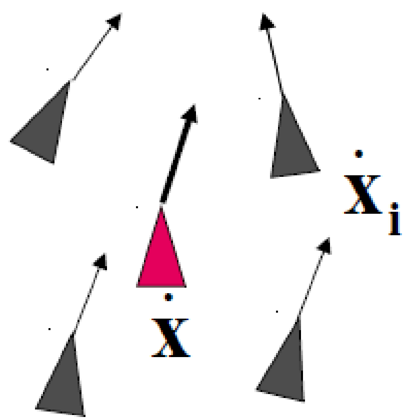


Separation:
Fly away away from neighbors that are “too close”

Alignment



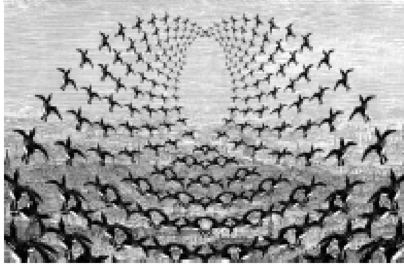
- Try to fly in same direction as local flock-mates
  - Gets everyone flying in the same direction



Alignment: steer toward average velocity

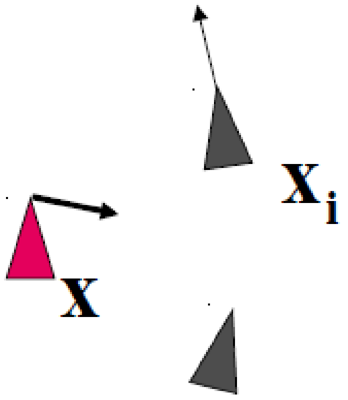
$$\mathbf{F}_A = \sum_{i \in S} \left(\dot{\mathbf{x}}_\mathbf{i} - \dot{\mathbf{x}} \right).$$

Cohesion



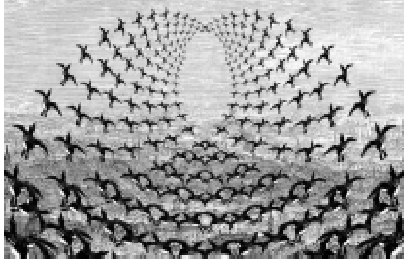
- Try to move toward the average position of local flock-mates
  - Spaces everyone out evenly,
  - keep boundary members toward the group

$$\mathbf{F}_C = \sum_{i \in S}^{N} \frac{\mathbf{x_i}}{N} - \mathbf{x}$$



Cohesion: steer toward average position

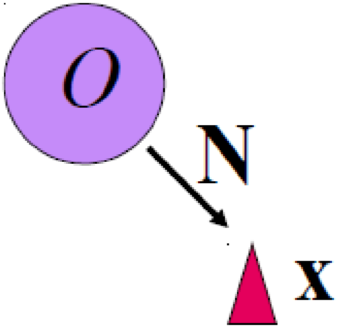
Avoidance



- Try to avoid obstacles
  - The closer the character is, the stronger the force

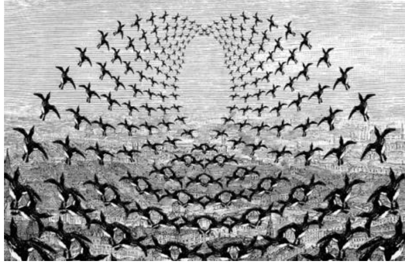
$$\mathbf{F}_O = \frac{\mathbf{N}}{D(O, \mathbf{x})}$$

$\mathbf{N}$: the normal vector of the obstacle at the point that is closest to $\mathbf{x}$



Avoidance: steer away from obstacles

Combining Commands



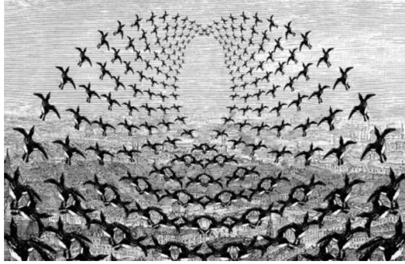
- Consider commands as accelerations
- Give a weight to each desire

w_S, w_C, w_A, w_O

  - Ex. High for avoidance, low for cohesion

Simply summing the weighted sum may cause issues

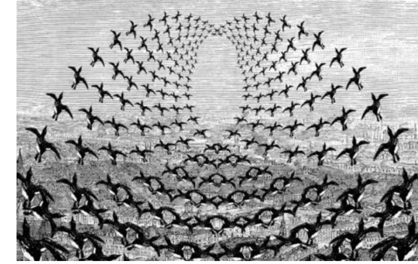
Combining Commands



- Option: Apply in order of highest weight, until a max (absolute sum of) acceleration is reached
  - Ensures that high priority things happen

$$w_O \gg w_S, w_C, w_A,$$

https://www.youtube.com/watch?v=4kPSDW7gQHA



Another application of flocking: Simulating dynamical features of escape panic : Helbing ‘00

- A model to simulate the crowd under panic

$$m_i \frac{d\vec{v}_i}{dt} = m_i \frac{\vec{v}_i^{\,o}(t)\vec{e}_i^{\,o}(t) - \vec{v}_i(t)}{\tau_i} + \sum_{j \neq i} \vec{f}_{ij} + \sum \vec{f}_{iw}$$

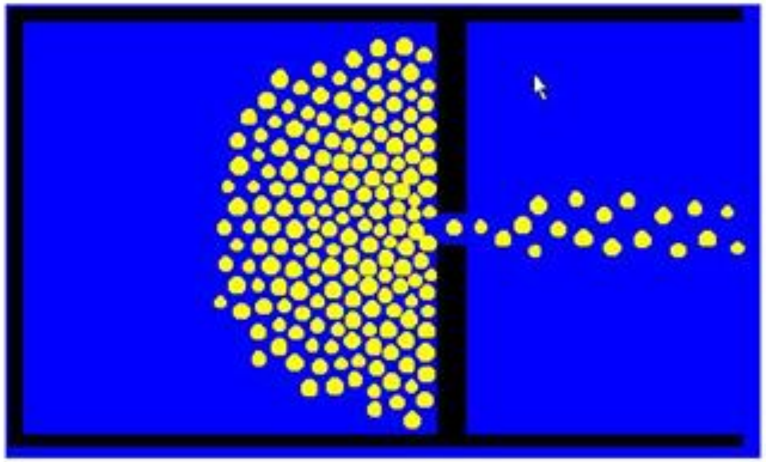
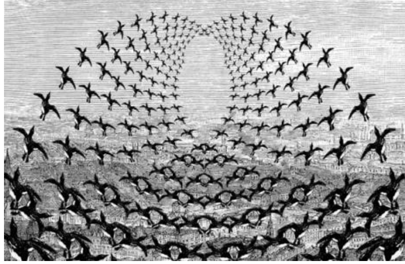


Figure 1: An image of Helbing´s Model Simulation.

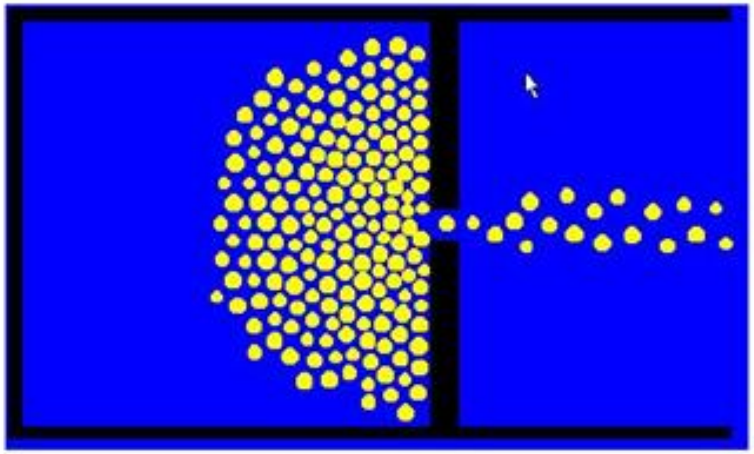
http://www.youtube.com/watch?v=mUKYtOXg5Zw

Simulating dynamical features of escape panic : Helbing '00



- f_{ij}, the force to stay away from other entities,
- f_{iw} the force to stay away from walls
- v_i: velocity of entity *i*
- $v_i^o e_i^o$: the desired velocity of entity *i*

$$m_i \frac{d\vec{v}_i}{dt} = m_i \frac{\vec{v}_i^{\,o}(t)\vec{e}_i^{\,o}(t) - \vec{v}_i(t)}{\tau_i} + \sum_{j \neq i} \vec{f}_{ij} + \sum \vec{f}_{iw}$$



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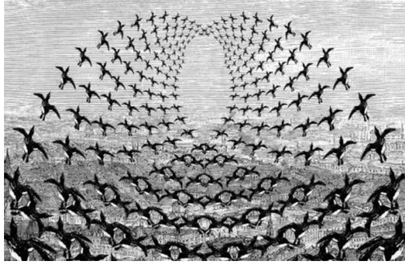
Simulating dynamical features of escape panic : Helbing ‘00



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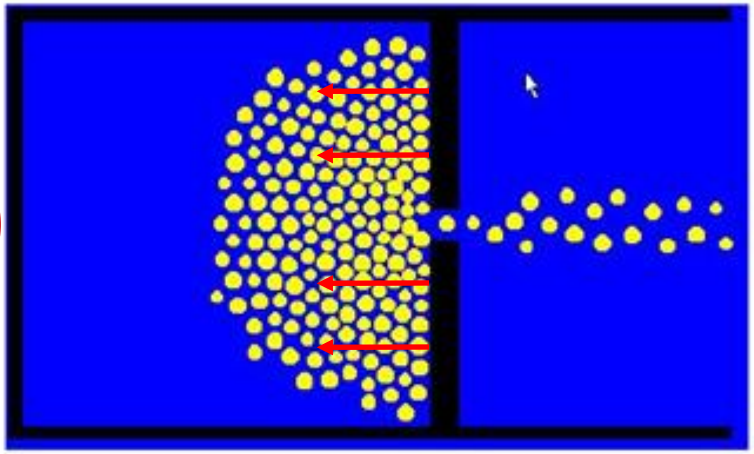

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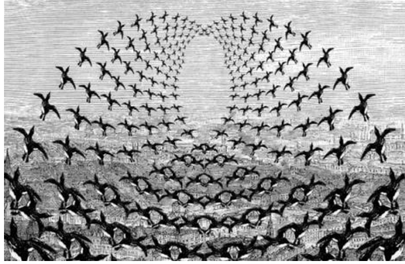

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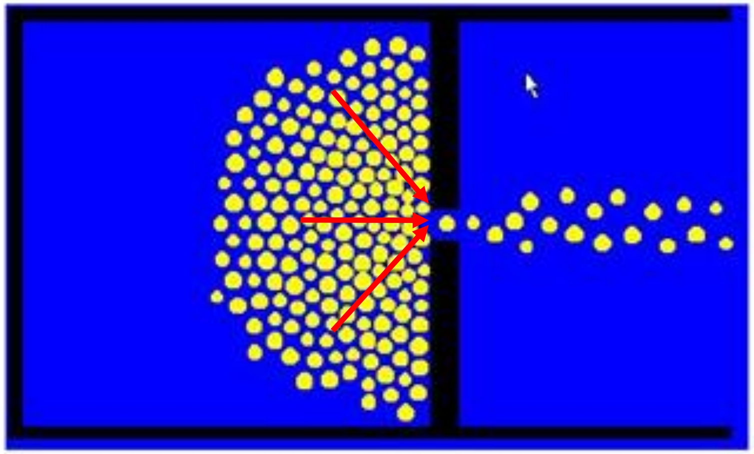

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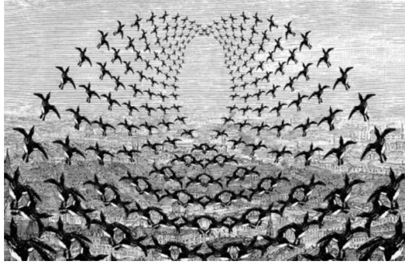
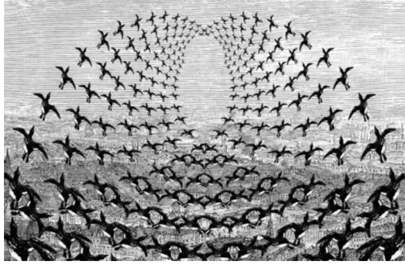
Flocking Evaluation



- Advantages:
  - Complex behaviour and phenomena from simple rules
  - Many types of behaviour can be expressed with different rules and parameters
- Disadvantages:
  - Can be difficult to set parameters to achieve desired result
  - Problems regarding strength of forces

Overview



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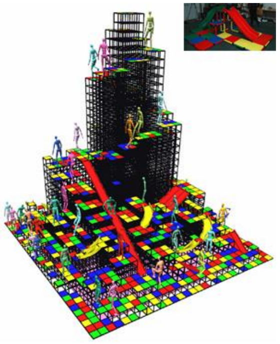
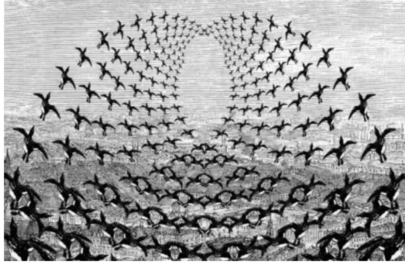
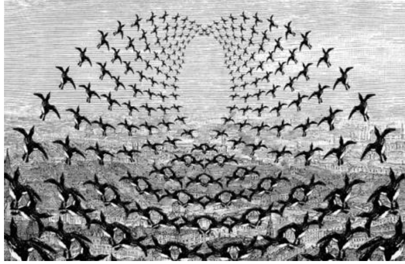


Making the Agents Smarter



- For animating realistic behaviours, higher level control is needed
  - e.g. Desired velocity of Helbing's system
  - What to do when you see a predator
  - What to do when you find somebody you know?
  - What to do when the traffic lights are red?
- Intention generator

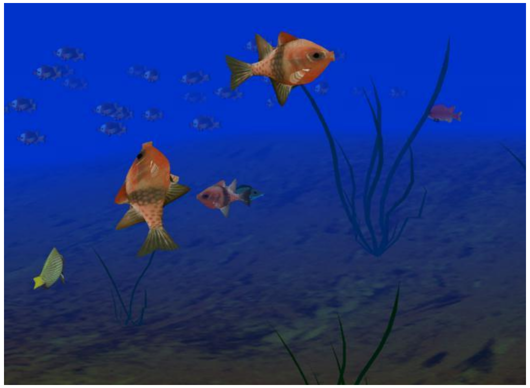
Artificial Fish
-Terzopoulos et al. SIGGRAPH '94



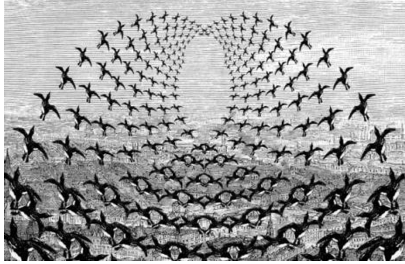
- Considering attributes such as
  - Hunger
  - Libido
  - Fear

for deciding the behaviour of the fish

- Adding sensory perception such as
  - Vision



Intention Generator



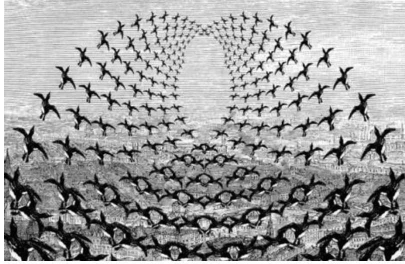
1. First check the sensory information for collision
2. If any close predator, either
   - School
   - Escape

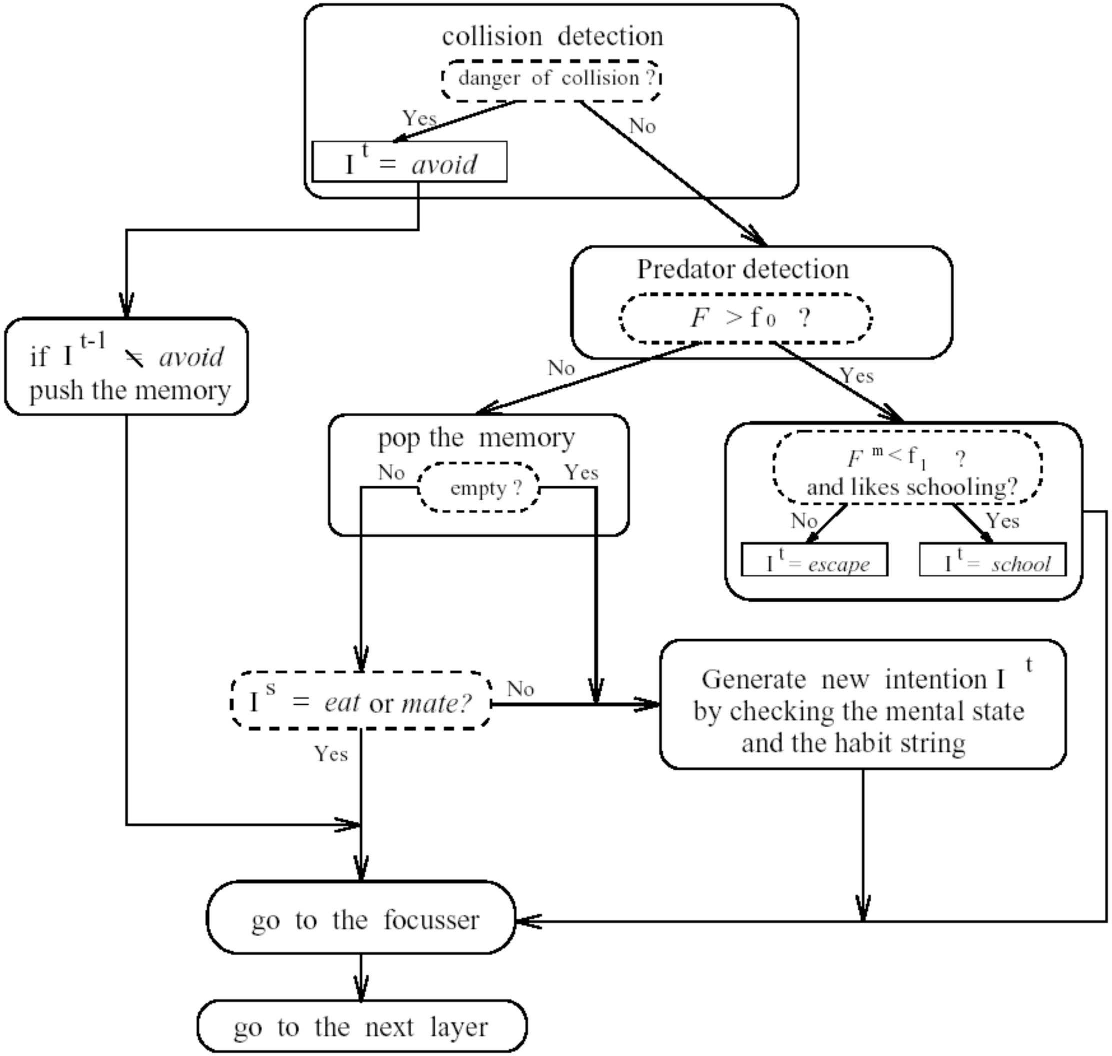
Otherwise if hungry eat

If full mate

http://www.youtube.com/watch?v=RHt_8ZYQVZw

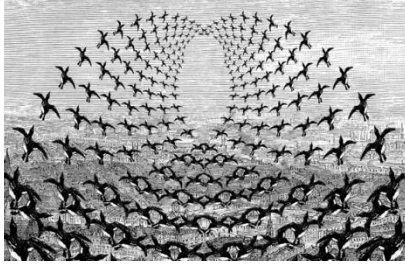
Intention Generator





- Decision making for the fish

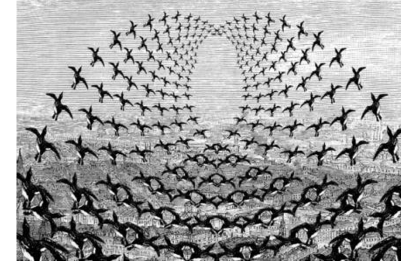
What about humans?



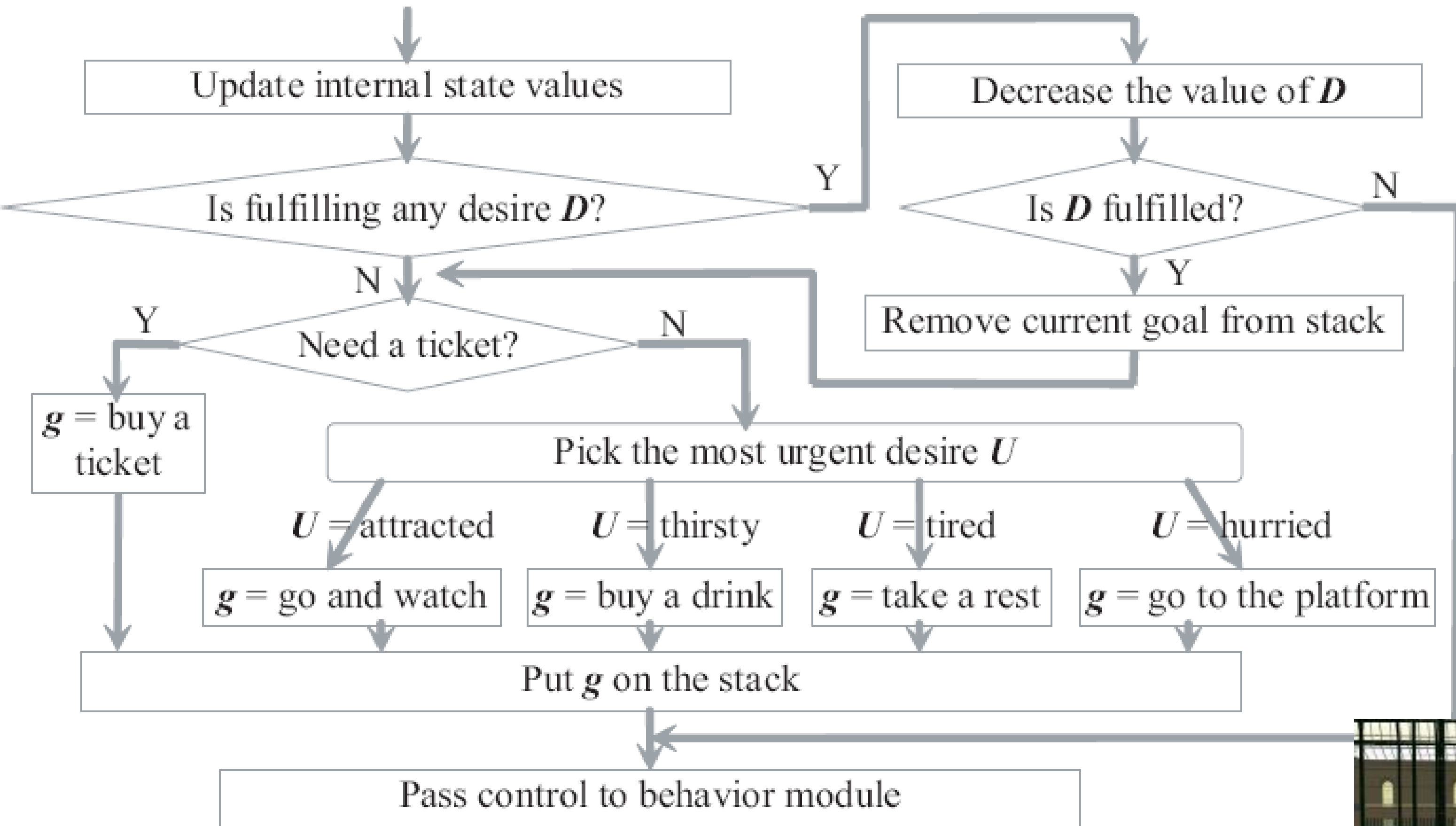
- Can do something similar
- But humans are a bit more high level
  - Not only eating or escaping
  - Have destinations
  - Contexts
  - Socializing
    - Grouping,
    - Talking to somebody you know

A more complex model is needed

Behavior model : Autonomous Pedestrians

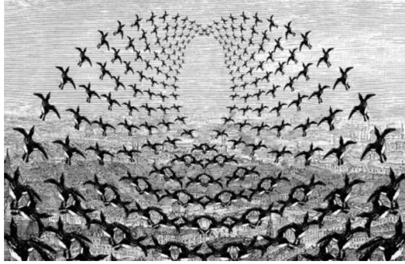


- More complex than a fish

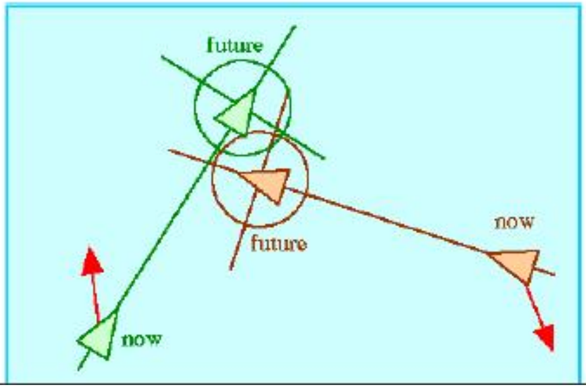


http://www.youtube.com/watch?v=cqG7ADSvQ5o

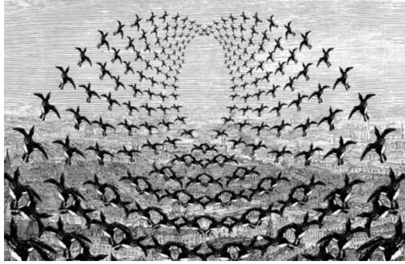
More serious problems for humans : context



- Interactions with the environment
- Collision avoidance
  - More complex than fishes
- Getting to the destination :
  - use path-finding algorithms such as A* search (shortest route to the destination)

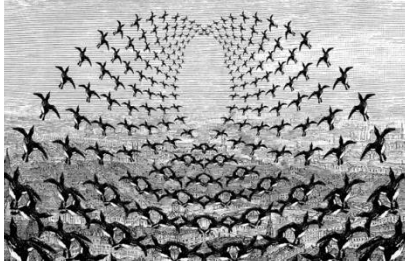


Interactions with the Environment



- Examples
  - At bus stops, people stop and queue
  - At an elevator, people wait for it and ride on it when it comes and travel to different floors
  - TV in the living room : turn on the TV and sit on the sofa to watch TV

Interactions with the Environment



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- **Preparing an intention generator to interact with all these objects is not so easy**

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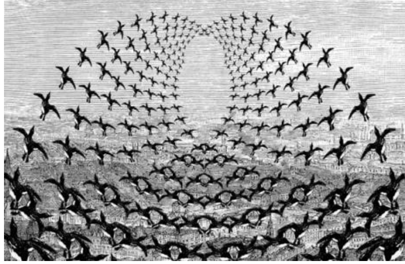

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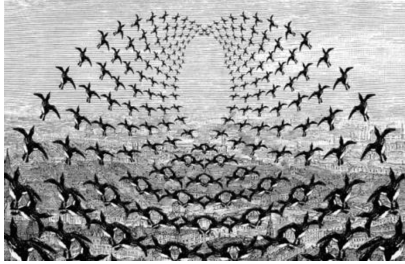

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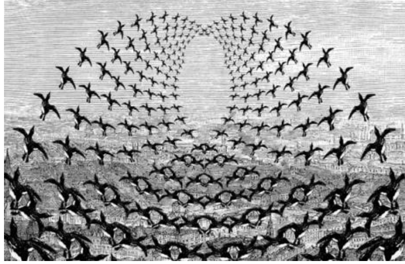
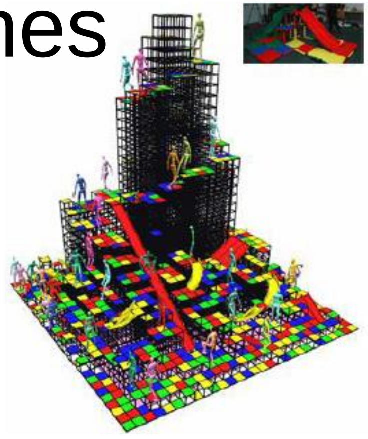
- Preparing an intention generator to interact with all these objects is not so easy
- Need various motion/object data

- **IDEA:** associate such motions with the objects
  - Once the character comes across such objects, they launch the associated motion

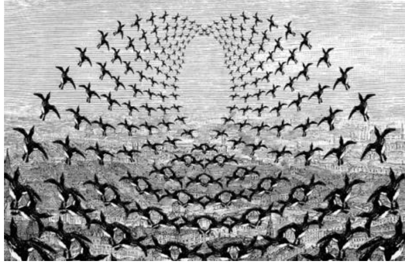


Patch-based approaches

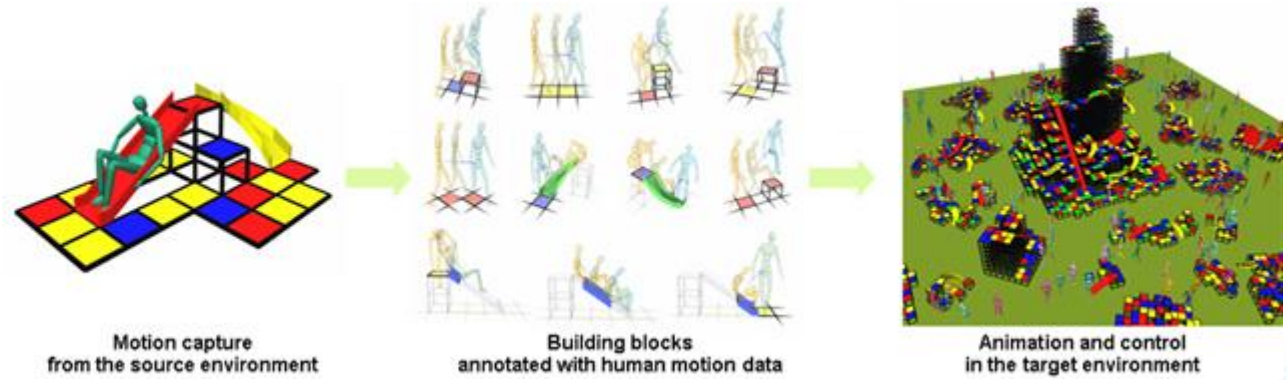
- Pre-compute the patches (building blocks) which include the characters and the environment
- Concatenate them to generate large scale scenes with multiple agents
  - Motion Patches
  - Crowd patches



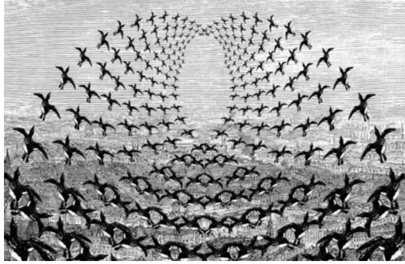
Motion Patches



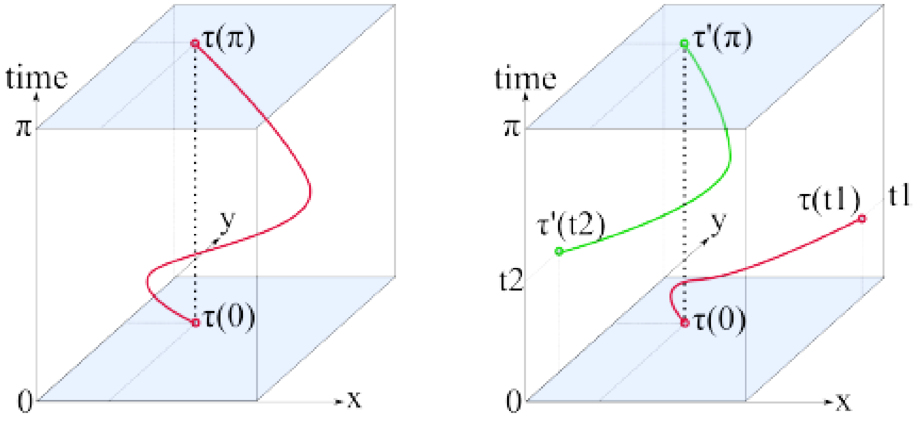
- Building Blocks for Virtual Environments
  - Embed the motions into the environment
  - The patches are spatially aligned

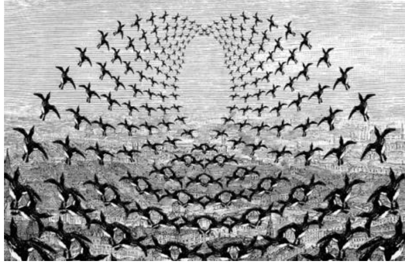


Crowd Patches



- A patch-based approach to generate scenes of crowded environment
- Crowds avoiding each other in the patches
- The timing and location the characters entering the patches are fixed so that the people can keep on entering / exiting
- The characters can be switched to make more variations





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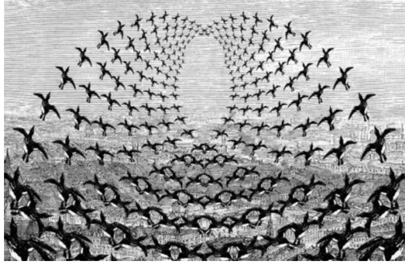
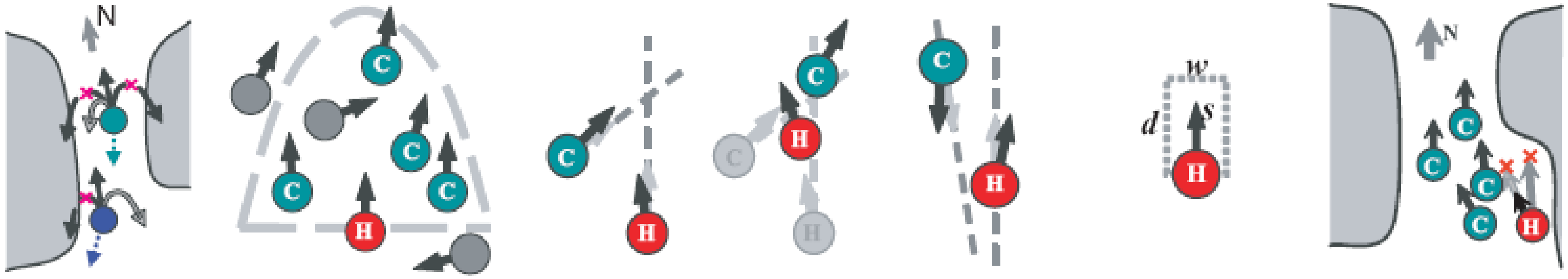
  - Flow-based approaches
  - Potential Field based approaches



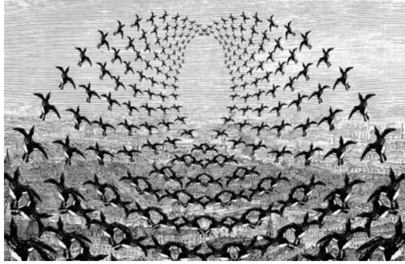
Collision avoidance

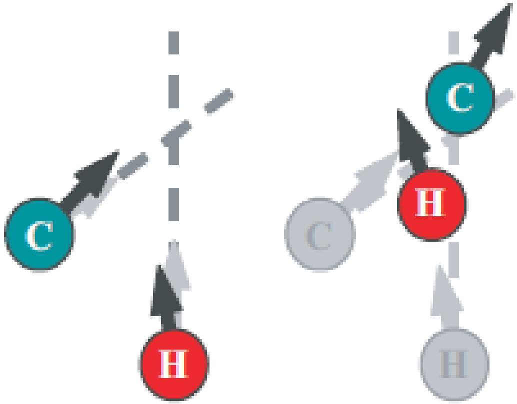
- Humans avoid others in streets in a complex way
- Sometimes wait, sometimes, move aside while walking
- Need to either
  - Extend the flocking model to produce realistic behaviours
  - Find a good mathematical model



(B) Safety in turning (C) Temporary crowd (D1) Cross collision (D2) Head-on coll'n (E) Front safe area (F) Verify direction

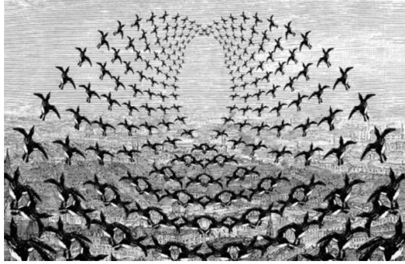
Avoid oncoming pedestrians

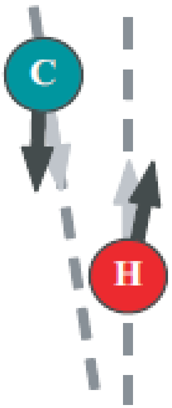




- If a cross collision is estimated by H with C
  - If H is arriving slightly earlier, it accelerates and turn away from C
  - If H is arriving slightly later, it decelerates and turn towards C
  - So C does the same

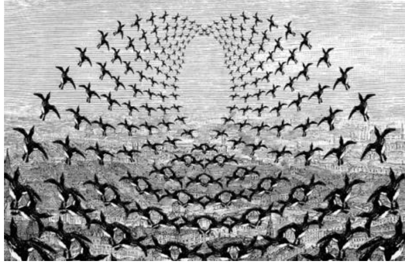
Head-on collision

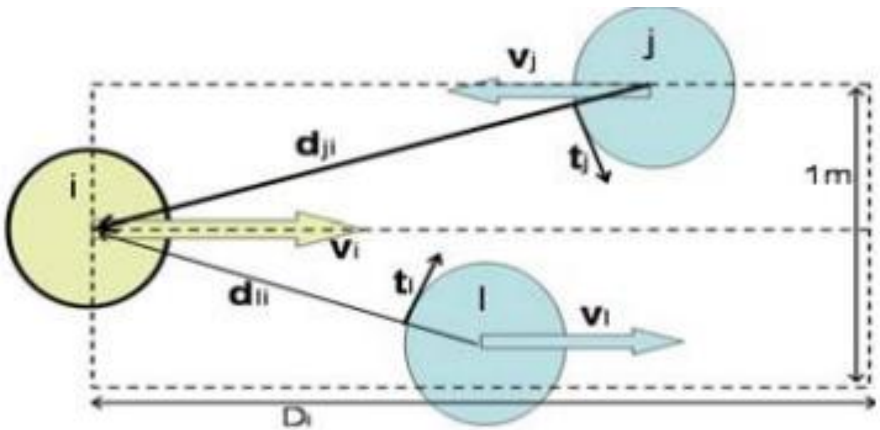




- If a head-on collision is estimated, the agents turn away from each other

Enhancing Flocking to Produce Realistic Crowd Movements

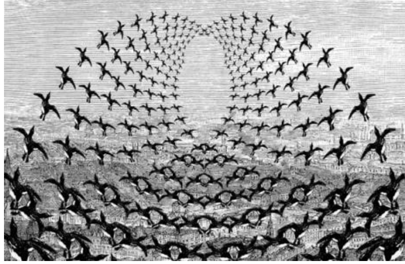




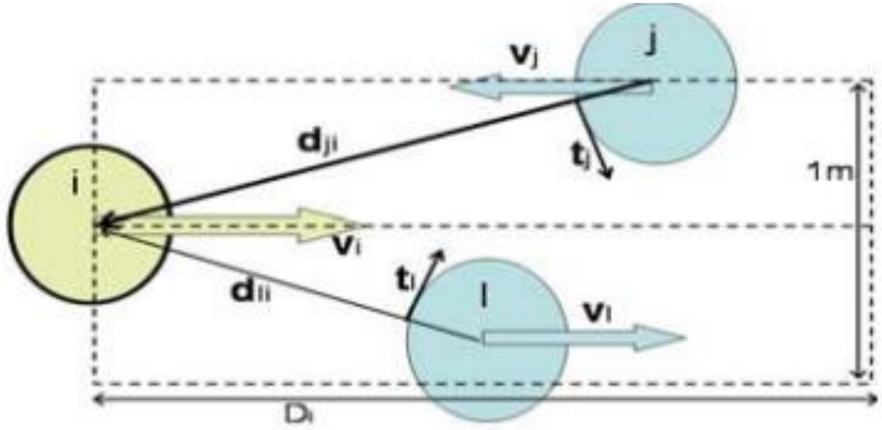
$$\mathbf{t}_j = \frac{(\mathbf{d}_{ji} \times \mathbf{v}_i) \times \mathbf{d}_{ji}}{\left|(\mathbf{d}_{ji} \times \mathbf{v}_i) \times \mathbf{d}_{ji}\right|}$$

- Defining a rectangular region that emulates human vision
- Compute the tangent force to avoid collisions

Enhancing Flocking to Produce Realistic Crowd Movements



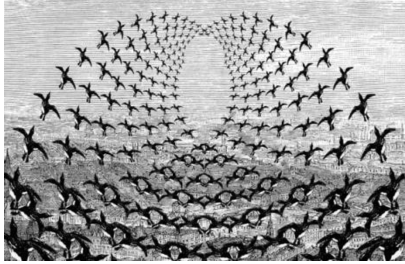
We want the force to be inverse proportional to the distance and relative velocity



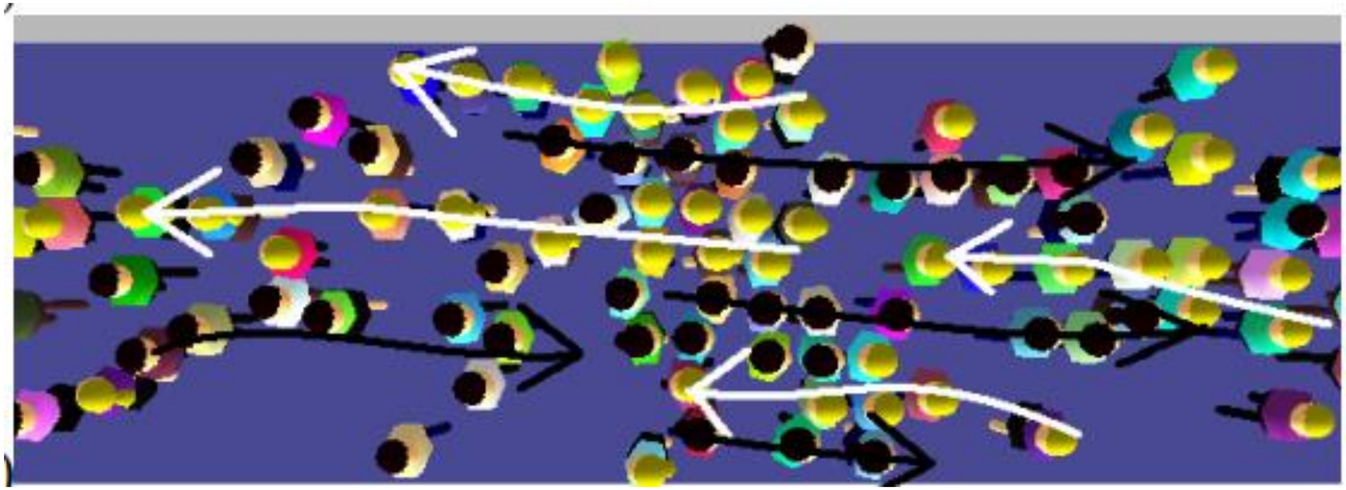
$$\mathbf{F}_{ji}^{Ot} = \mathbf{t}_j w_i^d w_i^o$$

$$w_i^o = \begin{cases} 1.2 & if\left(\mathbf{v}_i \cdot \mathbf{v}_j\right) > 0 \\ 2.4 & otherwise \end{cases}$$

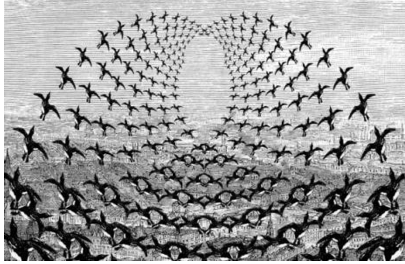
Enhancing Flocking to Produce Realistic Crowd Movements



- This results in interesting emergent counter-flow behaviour for high-density crowds
- Formation of lanes of people moving in the same direction intermingled among lanes moving in the opposite direction

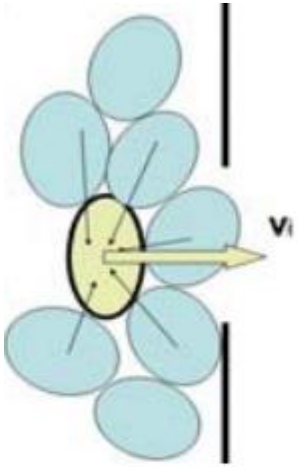


Enhancing Flocking to Produce Realistic Crowd Movements

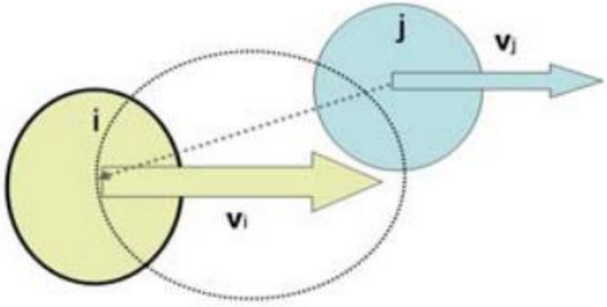


Stopping Rules:

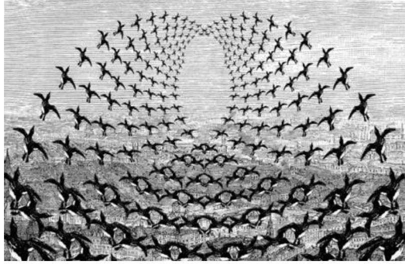
When the repulsion force from the others are against the desired direction of the agent, apply the stopping rule.



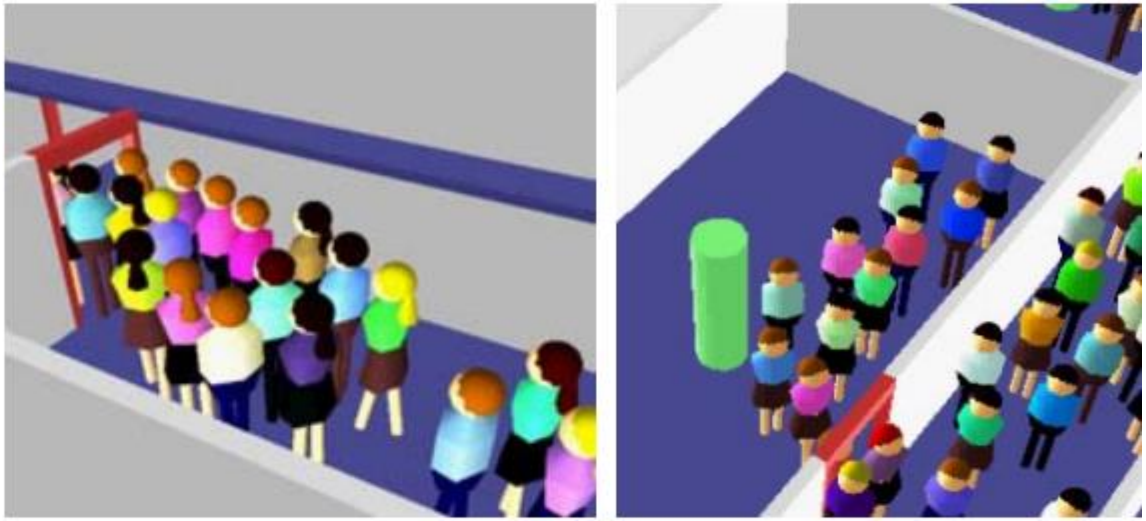
Also, when there are other agents in the influence area, stop the agent.

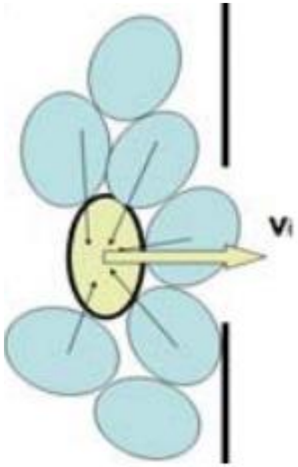


Enhancing Flocking to Produce Realistic Crowd Movements

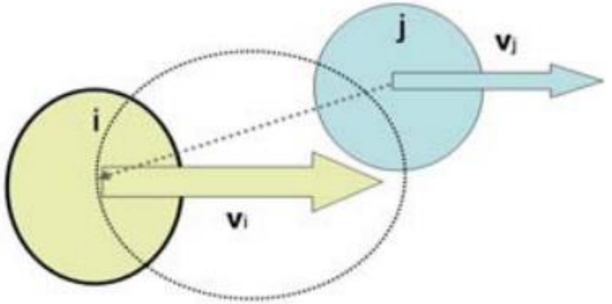


This produces realistic queuing behaviours

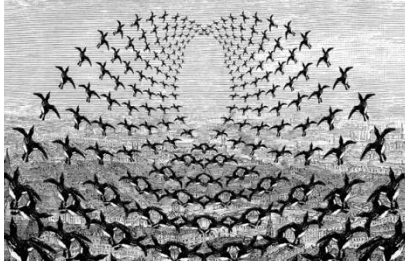




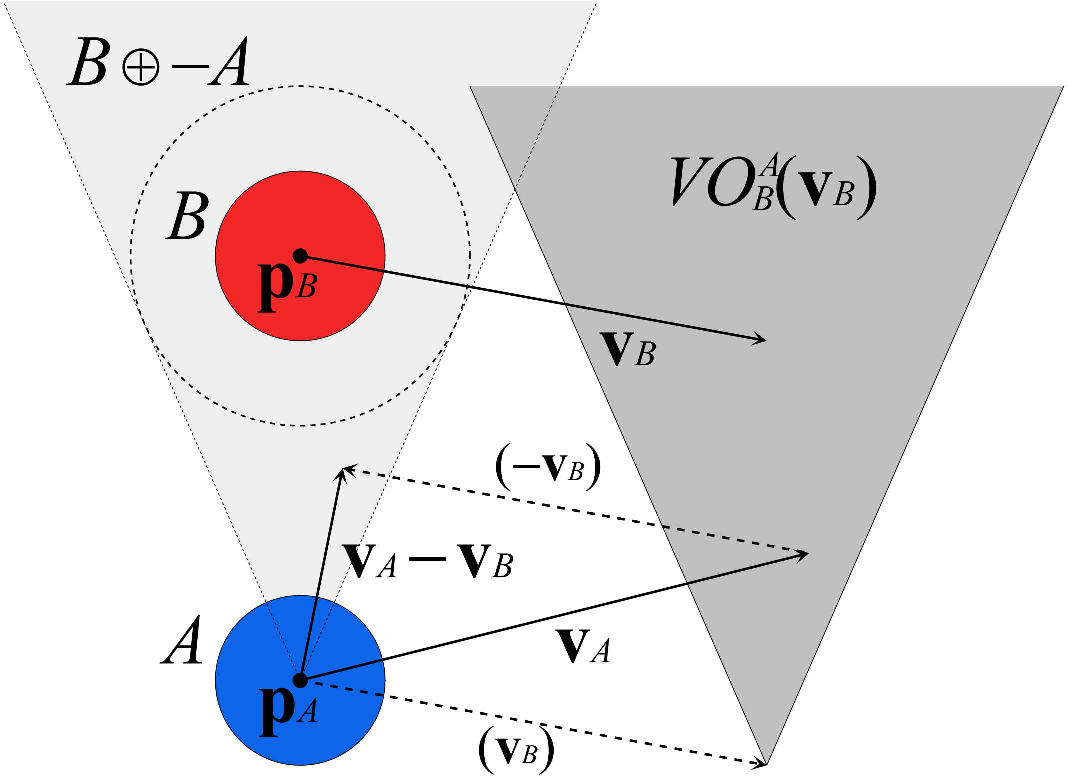
https://www.youtube.com/watch?v=KsbChtHmwfA



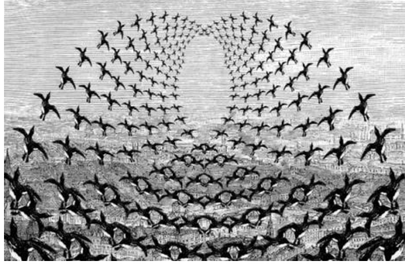
A Mathematical Model: Velocity Obstacle



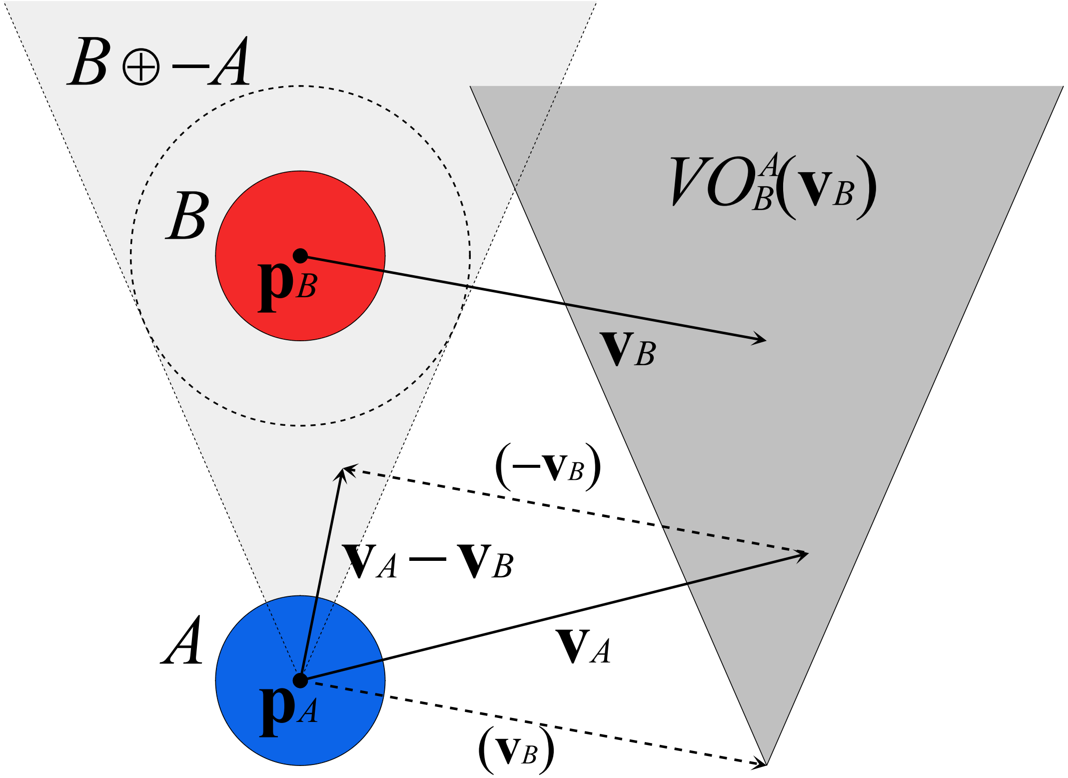
The set of all velocities of an agent that will result in a collision, assuming the other maintains its current velocity

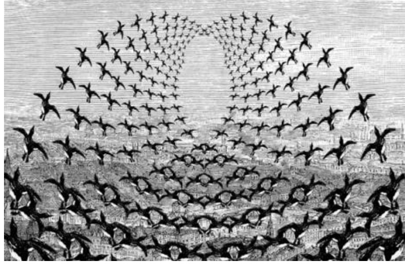


Velocity Obstacle (2)



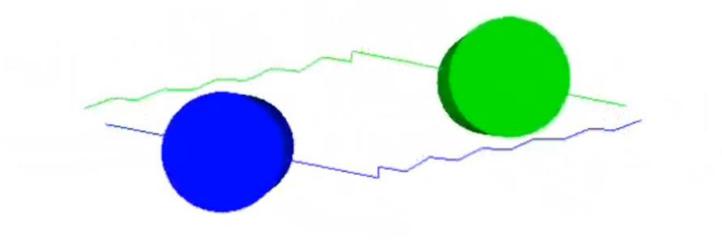
Strategy: Select a velocity that is closest to the desired velocity but outside the VO



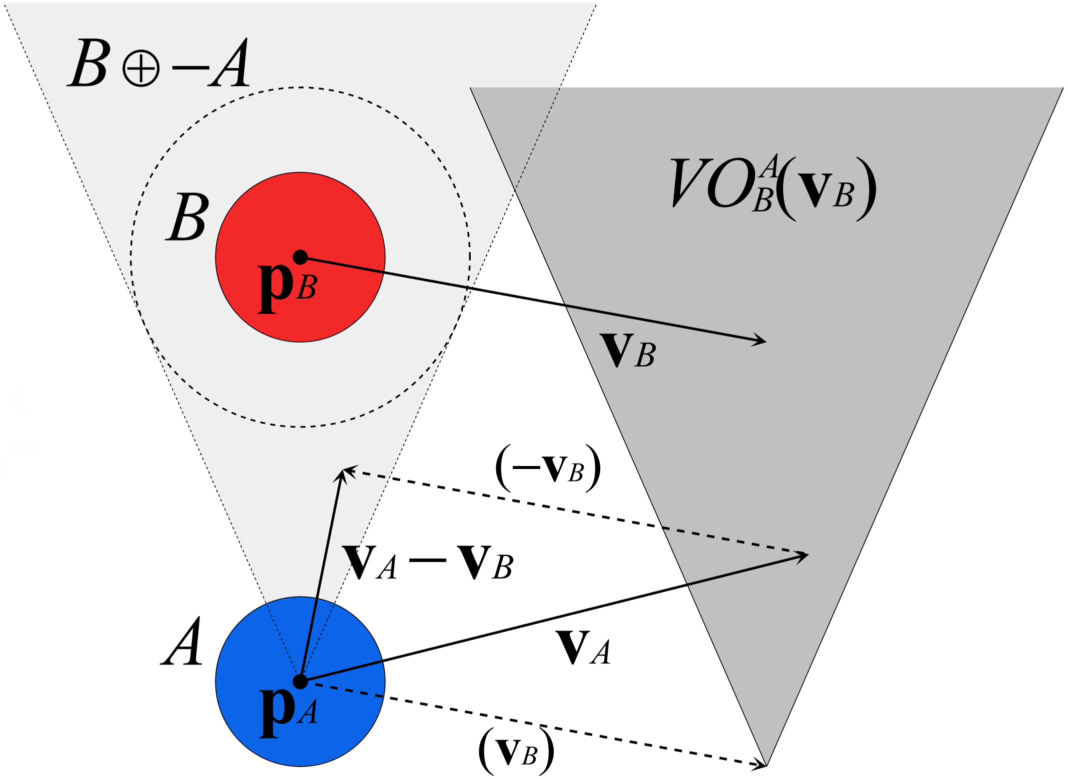


Velocity Obstacle (3)

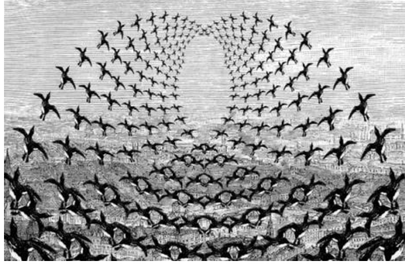
Good for collision avoidance, but can result in oscillation when both agents use the same strategy



http://youtu.be/BNTNpYTw3_s

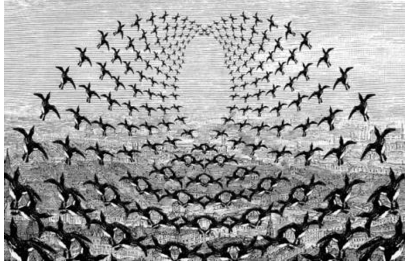


Reciprocal Velocity Obstacle (RVO)

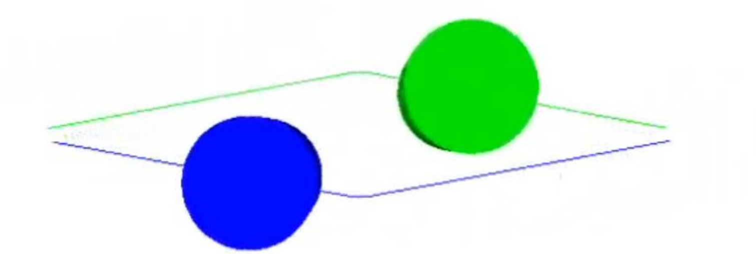


Idea: instead of choosing a new velocity outside the velocity obstacle, take the *average* of a velocity outside the velocity obstacle and the current velocity

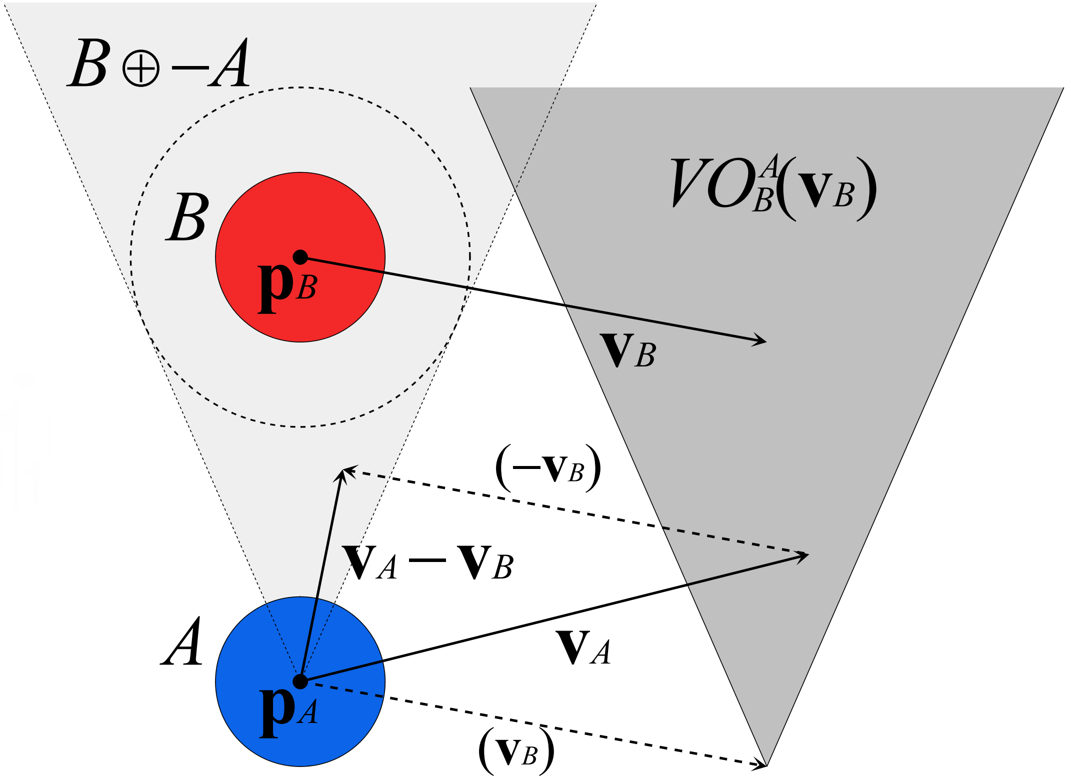
Reciprocal Velocity Obstacle (RVO)



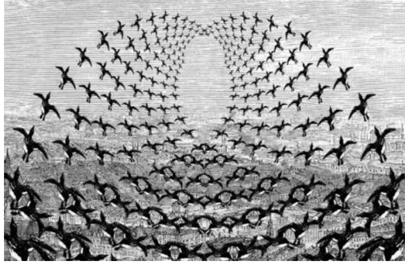
Idea: instead of choosing a new velocity outside the velocity obstacle, take the *average* of a velocity outside the velocity obstacle and the current velocity



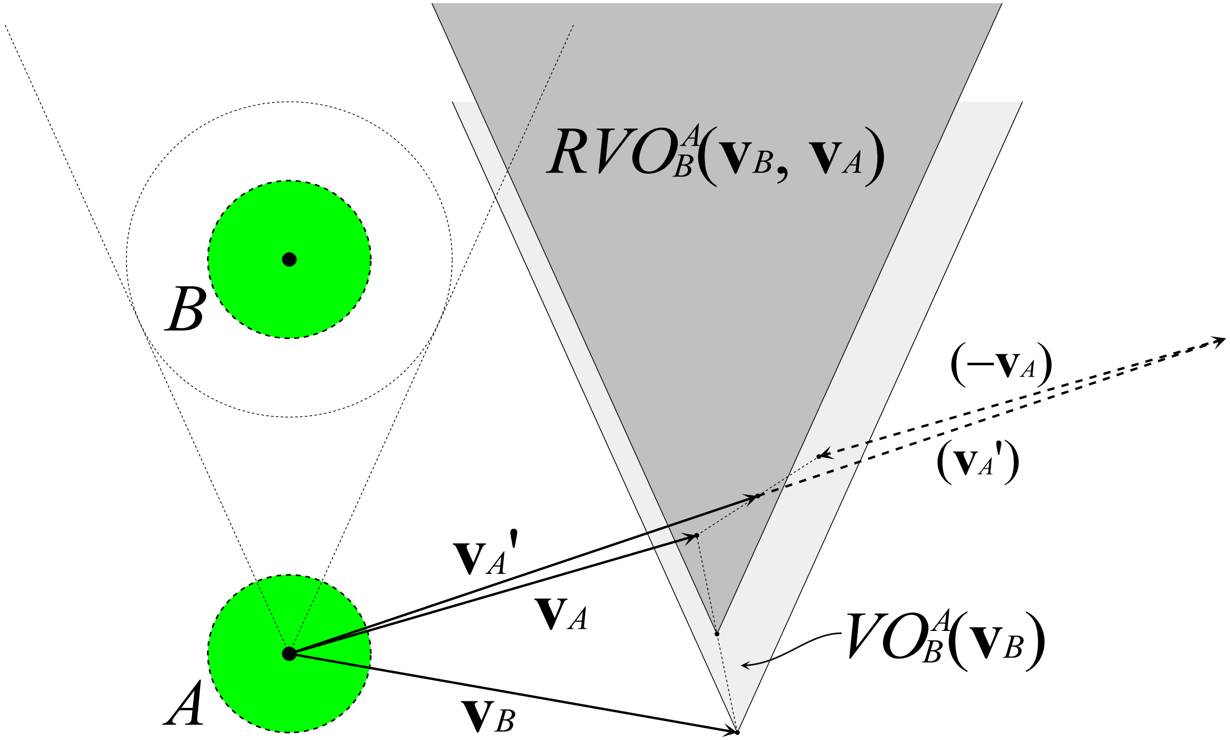
http://youtu.be/9O-YkaiBVXw



Reciprocal Velocity Obstacle (RVO)

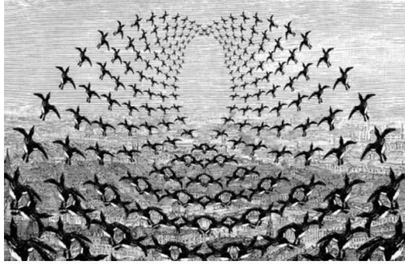


Idea: instead of choosing a new velocity outside the velocity obstacle, take the *average* of a velocity outside the velocity obstacle and the current velocity



$$RVO^A_B(v_B, v_A) = \{v'_A \mid 2v'_A - v_A \in VO^A_B(v_B)\}$$

Reciprocal Velocity Obstacle (RVO) (2)



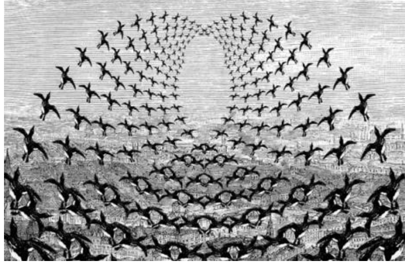
- No oscillation
- No global communication needed between the agents
- Simple and can handle multiple agents
  - Calculate the RVO with all the agents in the neighbours and select a velocity outside all the RVOs

http://youtu.be/JX_GaFpIcqo

http://youtu.be/soHH-ocT1V8

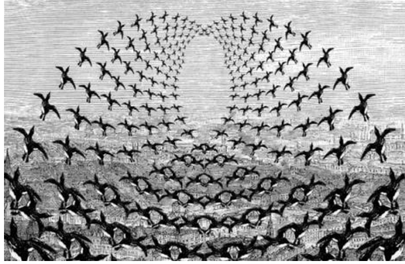
http://youtu.be/nZ4mVCZRD0E

Overview



- Agent based Methods
  - Flocking
  - Intention generator
  - Creating scenes with human crowds
  - Patch-based methods
    - Create scenes by building blocks
  - (Local) Collision avoidance
    - Enhancing flocking to produce social behaviour
    - Velocity obstacle, reciprocal velocity obstacle
- **Global methods**
  - **Flow-based approaches**
  - **Potential Field based approaches**

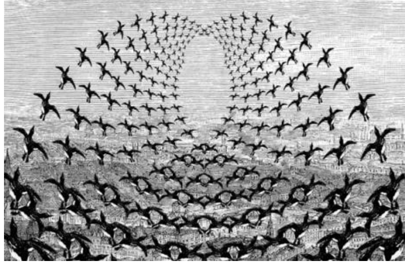
Collision Avoidance : Local vs. Global



- Sometimes you are interested in designing the flow of people rather modelling the behavior of the individual agents

→ Global Model

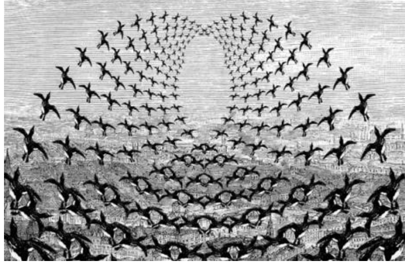
Global Models

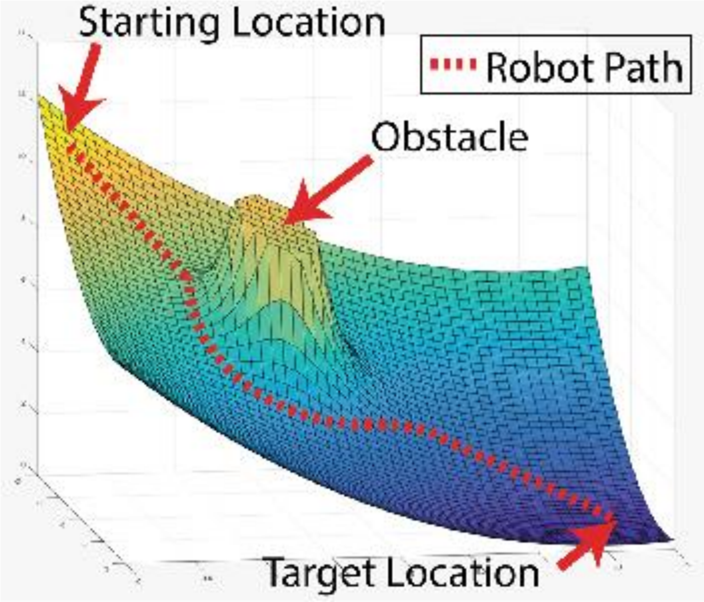


- Flow-based Models
  - Designing the crowd movements like flow fields (velocity fields)

- Potential Field-based Models
  - Designing potential fields that the agents simply need to follow the gradient of the field to reach the goal and avoid obstacles
    - Continuum Crowds

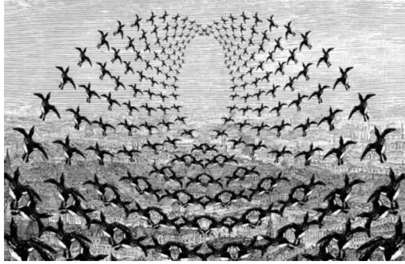
Potential Field-based approaches





- Generating a potential field that the agents simply need to follow the gradient to reach the goal
- Used in robotics a lot for navigating ground robots

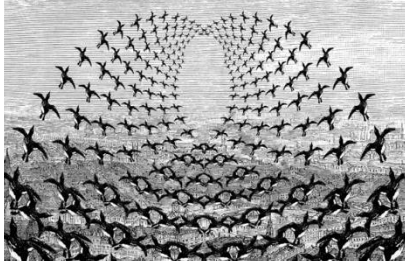
Continuum Crowds



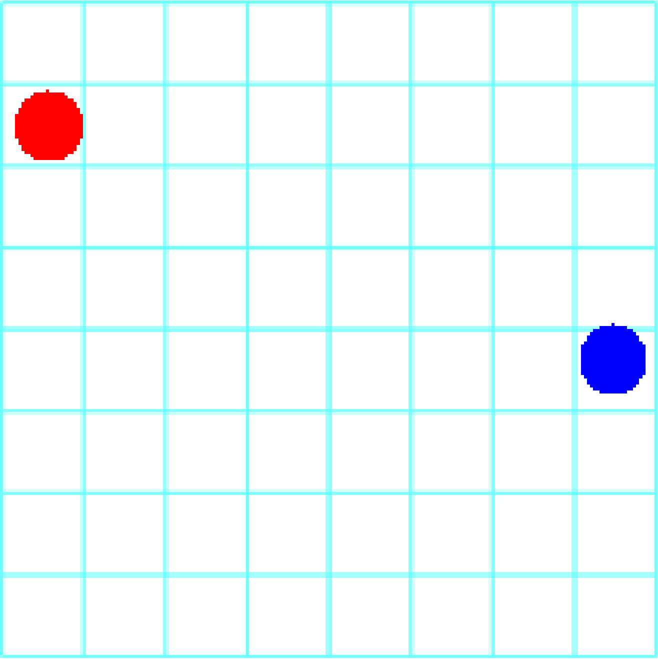
- Solving the path-planning and collision avoidance at the same time

1. Compute the potential field at every time step
   - Based on the other avatars and obstacles
   - The goal location
2. The character's movement determined based on the potential field
3. Update the potential field

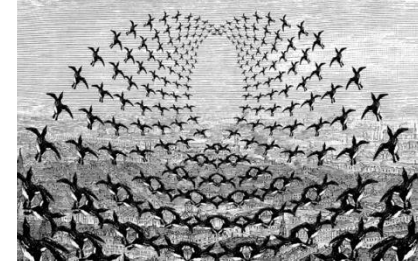
Continuum Crowds : procedure



- Discretize the space into grids
- Decide the start / goal of the characters



Continuum Crowds : procedure 2

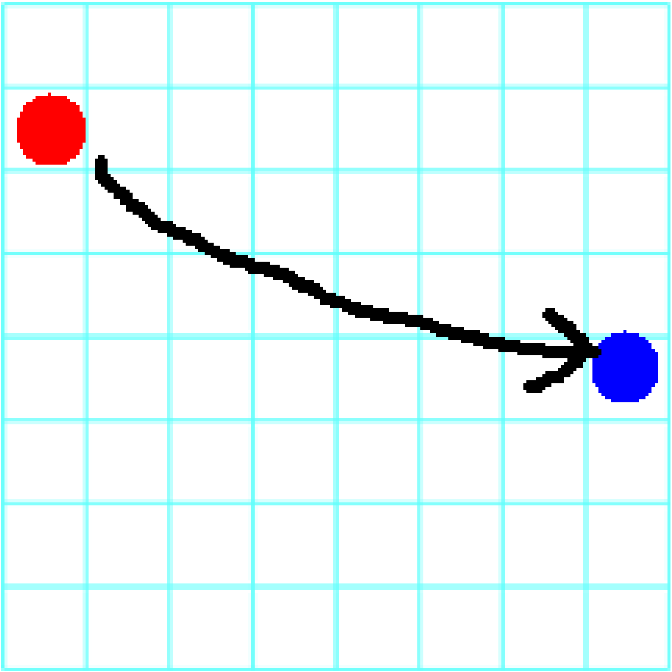


- The cost to the goal is going to be computed by the following function:

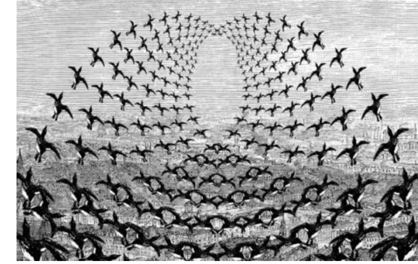
$$\underbrace{\alpha \int_P 1 ds}_{\text{Path Length}} + \underbrace{\beta \int_P \frac{1}{f} ds}_{\text{Time}} + \underbrace{\gamma \int_P \frac{g}{f} ds}_{\text{Discomfort}}$$

$$\int_P C ds, \quad \text{where} \quad C \equiv \frac{\alpha f + \beta + \gamma g}{f}$$

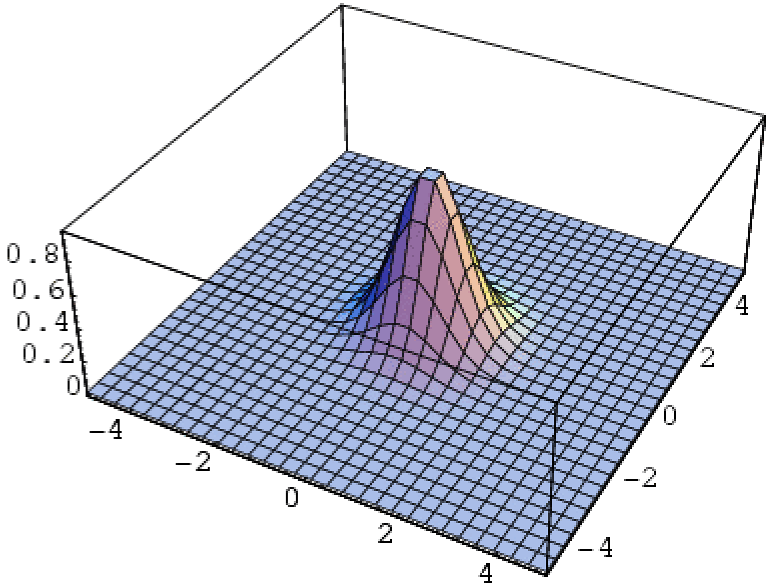
speed

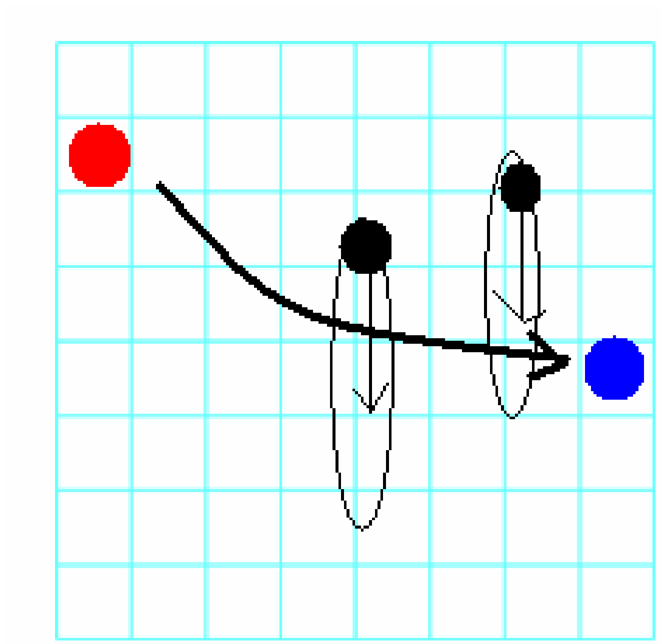


Discomfort Field



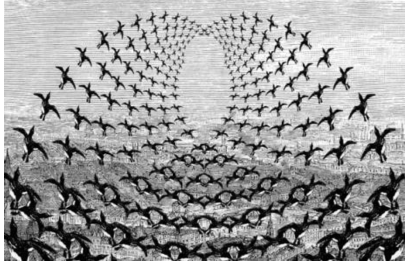
- Produced by other obstacles / characters

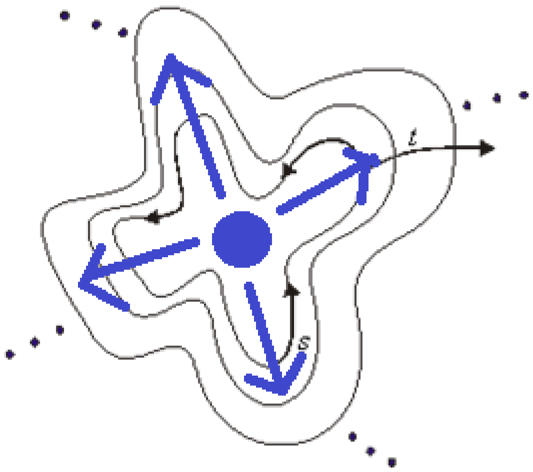




$$\underbrace{\alpha \int_P 1\,ds}_{\text{Path Length}} + \underbrace{\beta \int_P \frac{1}{f}\,ds}_{\text{Time}} + \underbrace{\gamma \int_P \frac{g}{f}\,ds}_{\text{Discomfort}}$$

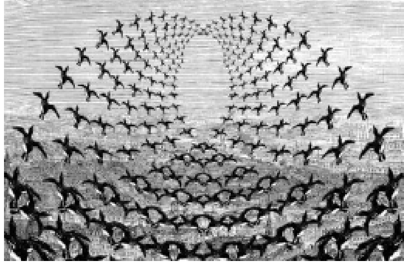
Continuum Crowds : procedure 2





- Starting from the goal we expand outwards and accumulate the cost *C*
  - *Fast Marching Method*
  - Similar to Djikstra’s algorithm

Fast Marching Method

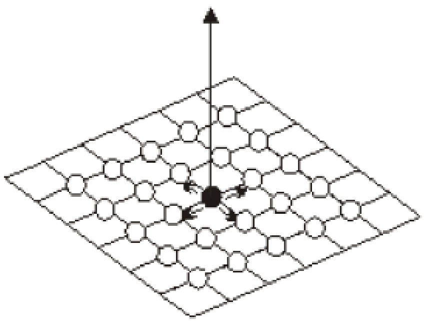
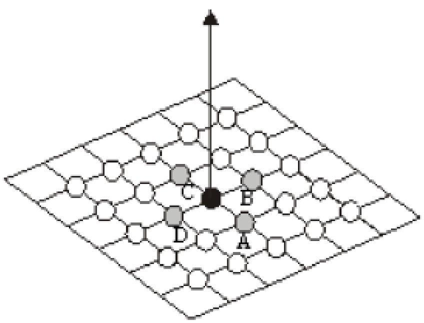


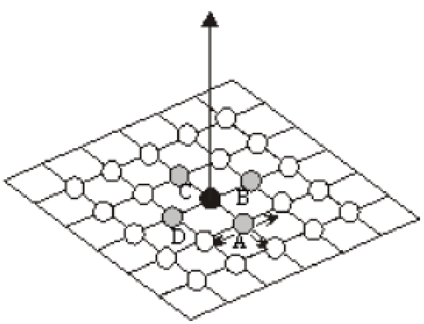
Initialize Step : Put the goal in the Alive Points

Alive Points (A): The set of points we know the cost ($T_{i,j}$)

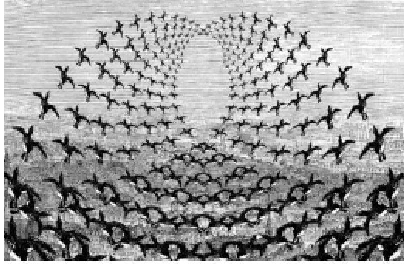
Narrow Band: grid points neighbors of A.

Far Away Points: all others grid points {i,j}. Set the cost ($T_{i,j}$) ∞ for all points in FarAway.

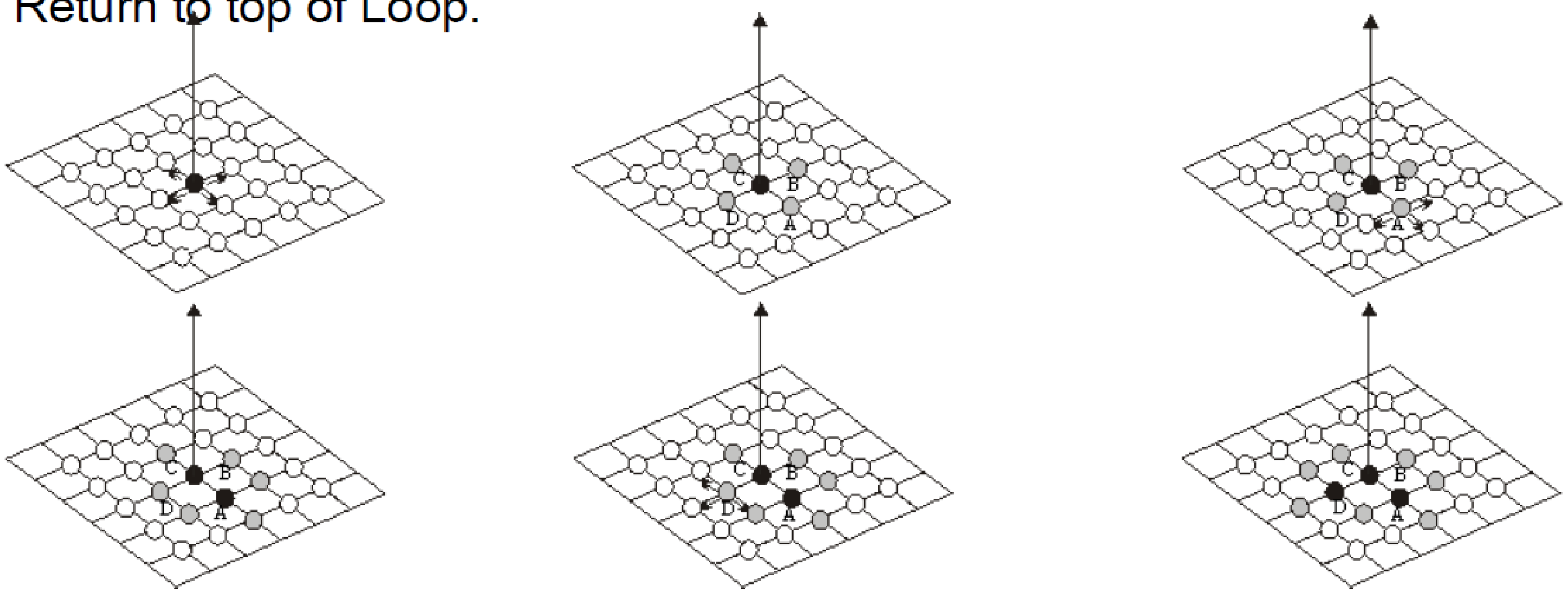


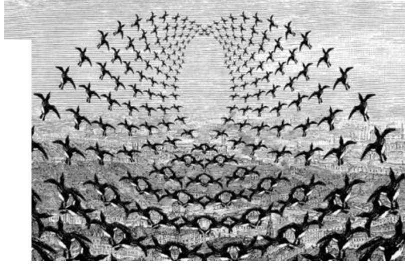
Marching Forwards



1. Begin Loop: Let (i_{min}, j_{min}) be the point in NarrowBand with the smallest value for Ø (cost)
2. Add the point (i_{min}, j_{min}) to A; remove it from NarrowBand.
3. Tag as neighbors any points $(i_{min}-1, j_{min})$, $(i_{min}+1, j_{min})$, $(i_{min}, j_{min}-1)$, $(i_{min}, j_{min}+1)$ that are either in NarrowBand or FarAway. If the neighbor is in FarAway, remove it from that list and add it to the set NarrowBand.
4. Recompute the values of Ø at all neighbors

Return to top of Loop.





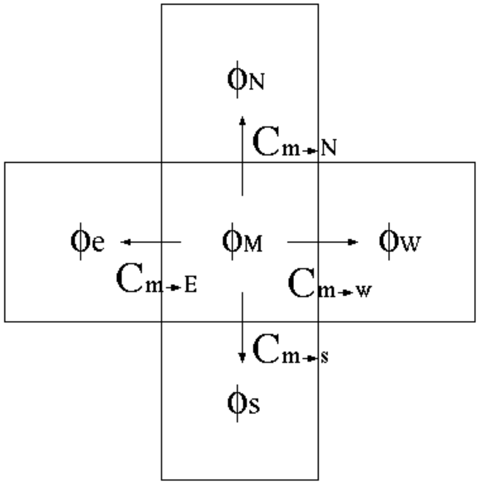
Computing the values of ∅

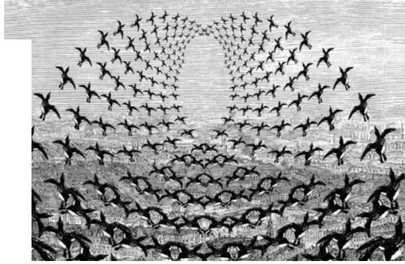
- Use the Eikonal equation

$$||\nabla \phi(\mathbf{x})|| = C,$$

- Among the adjacent grid cells, we first find those with less cost

$$m_x = \operatorname*{argmin}_{i \in \{W,E\}} \{\phi_i + C_{M \to i}\} \qquad m_y = \operatorname*{argmin}_{i \in \{N,S\}} \{\phi_i + C_{M \to i}\}.$$



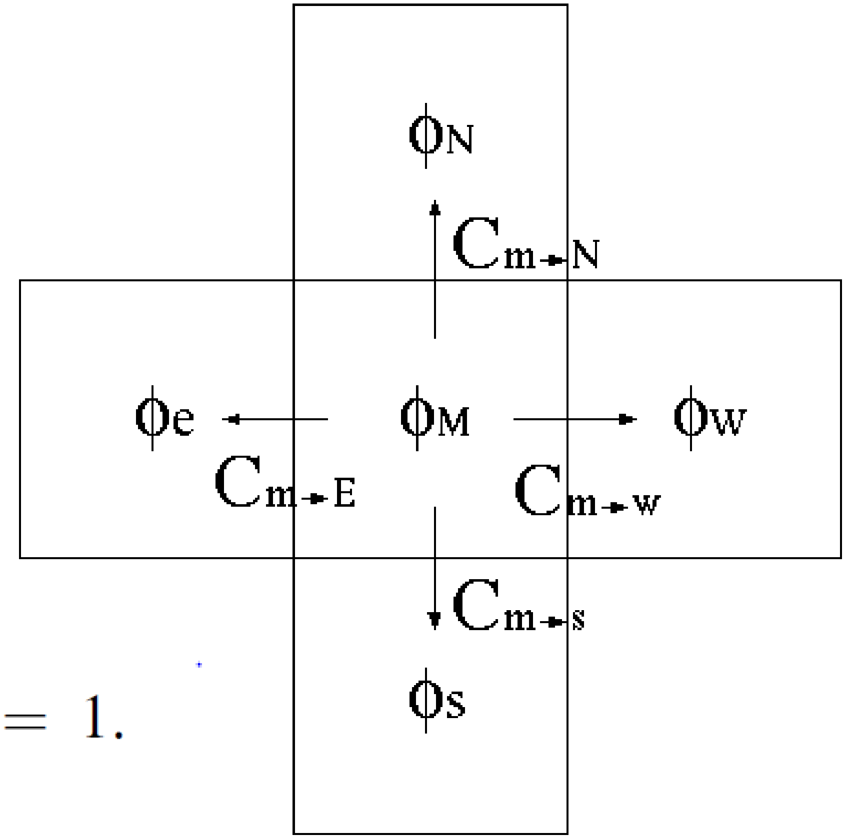


Computing the values of ø (2)

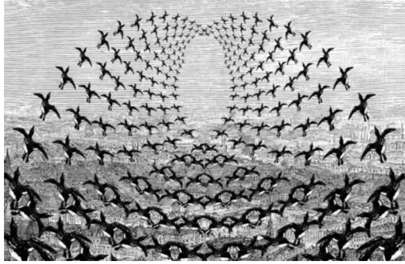
- Compute Φ by solving the Eikonel function with finite difference

$$||\nabla\phi(\mathbf{x})|| = C,$$

$$\left(\frac{\phi_M - \phi_{m_x}}{C_{M\rightarrow m_x}}\right)^2 + \left(\frac{\phi_M - \phi_{m_y}}{C_{M\rightarrow m_y}}\right)^2 = 1.$$

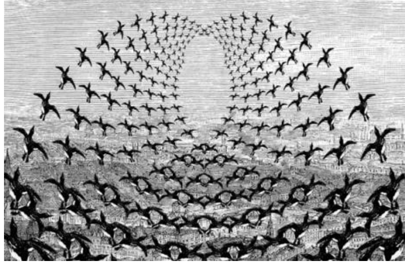


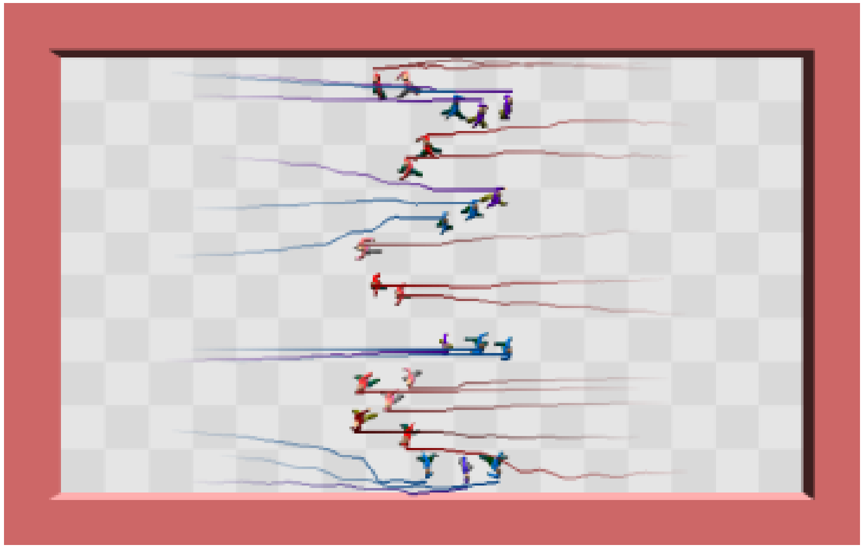
Potential Field

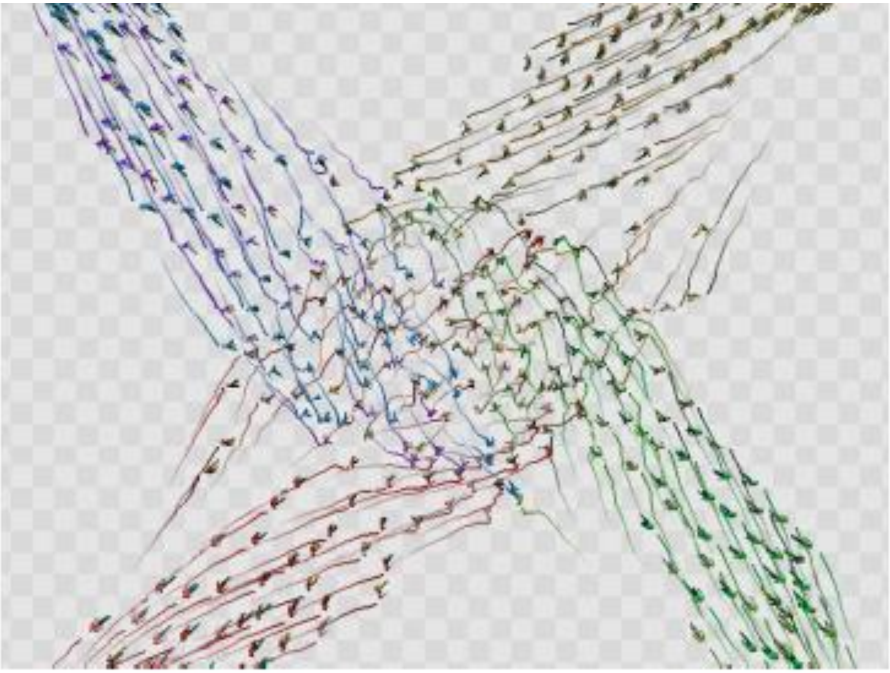


- If the group of people share the same speed, goal, and discomfort, we can use the same potential field for all these characters
  - Very efficient if there are little number of groups

Can simulate the dynamics of crowds



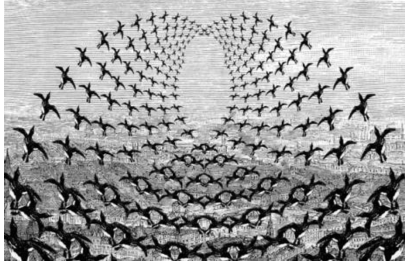




- A global approach (optimal towards the goal)
- Can simulate phenomena observed in real humans

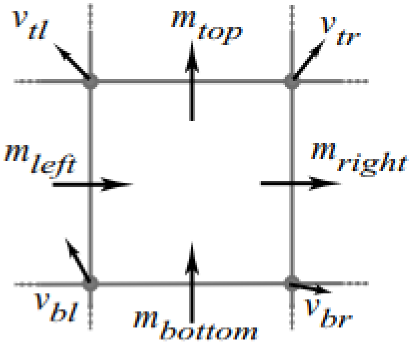
http://www.youtube.com/watch?v=IqIuVhDFSp8

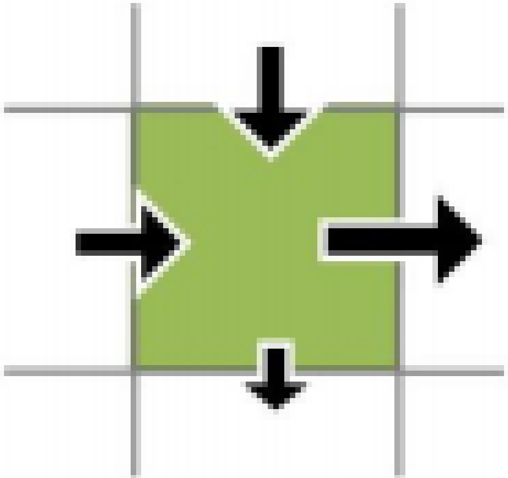
Flow-based Approaches

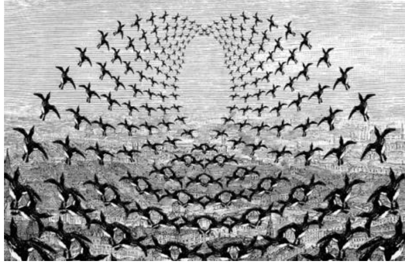


- We can assume the crowd flow is like fluid.
- Fluid are often incompressible (divergence free).
- The amount of people coming into a grid and going out must be the same.

$$m_{left} + m_{bottom} = m_{right} + m_{top}$$

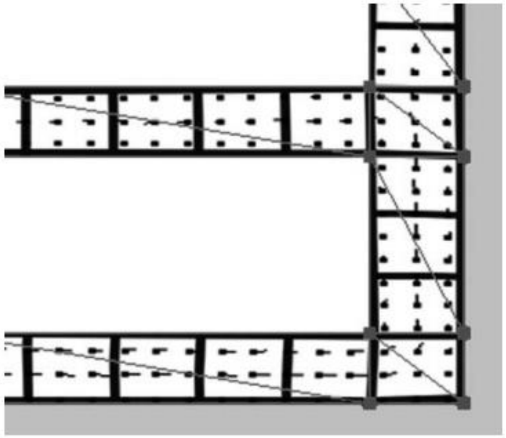


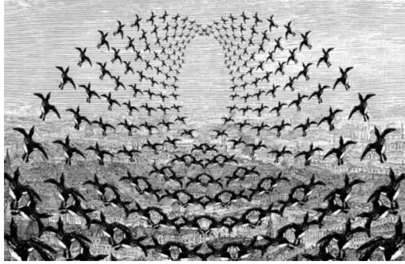




Flow Tiles

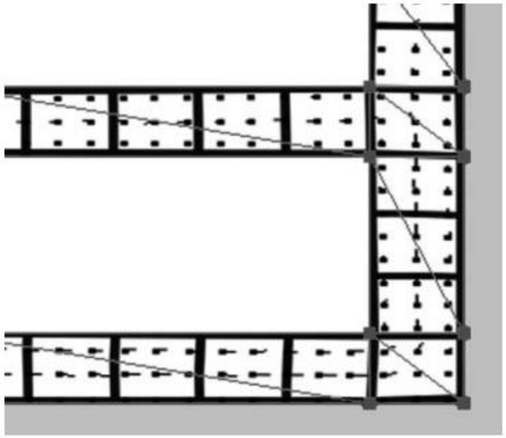
- We can design the flow by tiling flow-tiles.
- The adjacent tiles have the same input/output.
- The corner velocity must also match.
- Can manually design the entire scene, or manually specify a few tiles, and then do some optmization

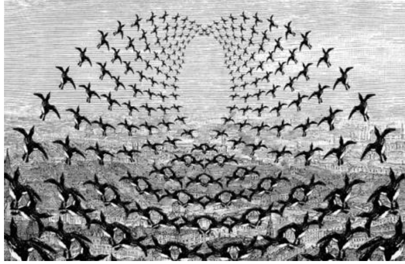




Flow Tiles

- Once the flow is decided, you can simply place characters and there will be no collisions
- Can allocate as many people as you wish

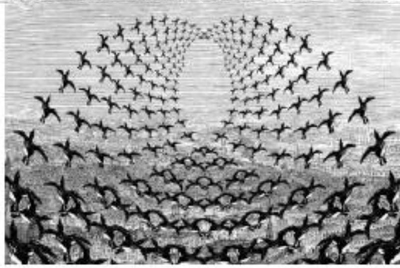




Flow-based Methods

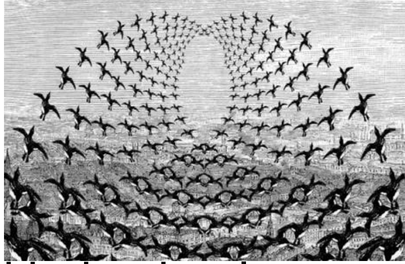
- Can also produce a dynamically changing flow to simulate very crowded scenes

Summary and Discussions



- Two streams
  - Agent-based
  - Global methods
- Applications
  - Animation, games
  - Evacuation analysis
- Collision avoidance is important not only for character animation but also for robotics

Reference



- REYNOLDS, C. W. 1987. Flocks, herds, and schools: A distributed behavioral model. In Computer Graphics (Proceedings of SIGGRAPH 87)
- TU, X., AND TERZOPOULOS, D. 1994. Artificial fishes: Physics, locomotion, perception, behavior. In Proceedings of SIGGRAPH 94, Computer Graphics Proceedings, Annual Conference Series, 43–50.
- SHAO, W., AND TERZOPOULOS, D. 2005. Autonomous pedestrians. In SCA '05: Proceedings of the 2005 ACM SIGGRAPH/Eurographics symposium on Computer animation, ACM Press, New York, NY, USA, 19–28.
- **Crowd Patches: Populating Large-Scale Virtual Environments for Real-Time Applications**. *Barbara Yersin, Jonathan Maïm, Julien Pettré and Daniel Thalmann.* ACM SIGGRAPH Symposium on Interactive 3D Graphics and Games 2009.
- Kang Hoon Lee, Myung Geol Choi and Jehee Lee, Motion Patches: Building Blocks for Virtual Environments Annotated with Motion Data, accepted to ACM SIGGRAPH 2006.
- Pelechano et al. Controlling Individual Agents in High-Density Crowd Simulation, SCA 2007
- Jur van den Berg, Ming C. Lin, Dinesh Manocha "Reciprocal Velocity Obstacles for Real-Time Multi-Agent Navigation" Proceedings of the IEEE International Conference on Robotics and Automation (ICRA), 2008.
- Adrien Treuille, Seth Cooper, Zoran Popovic, Continuum Crowds, SIGGRAPH 2005
- Chenney, “Flow Tiles”, SCA 2004