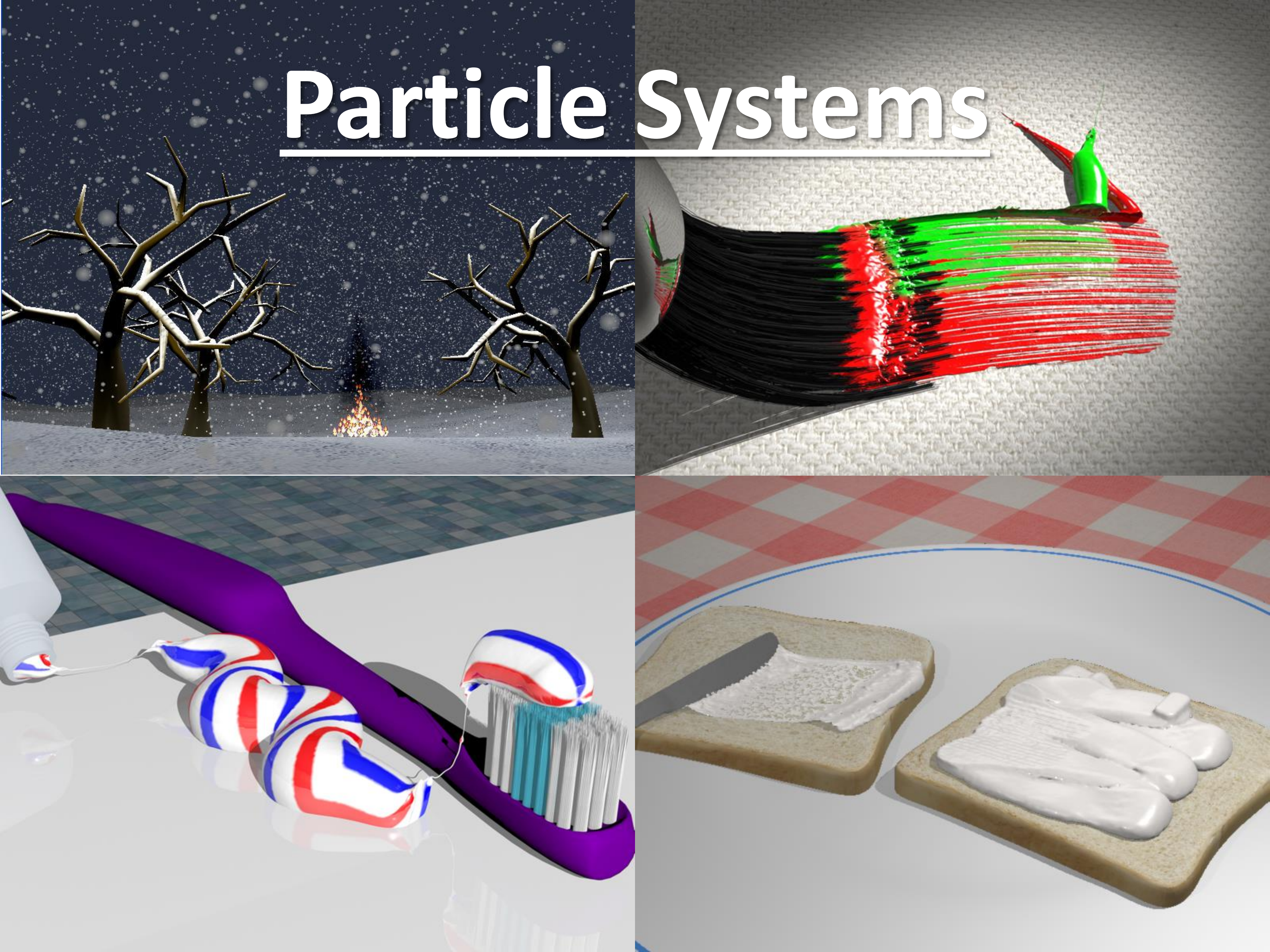
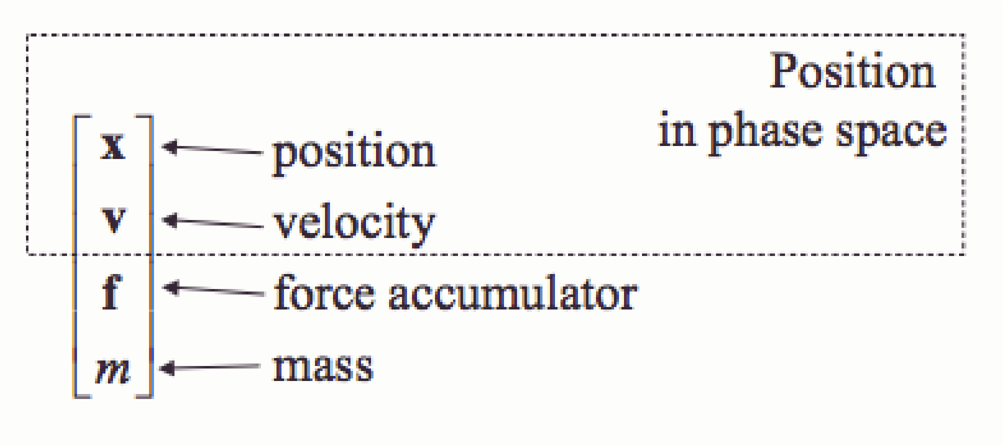
Particle Systems

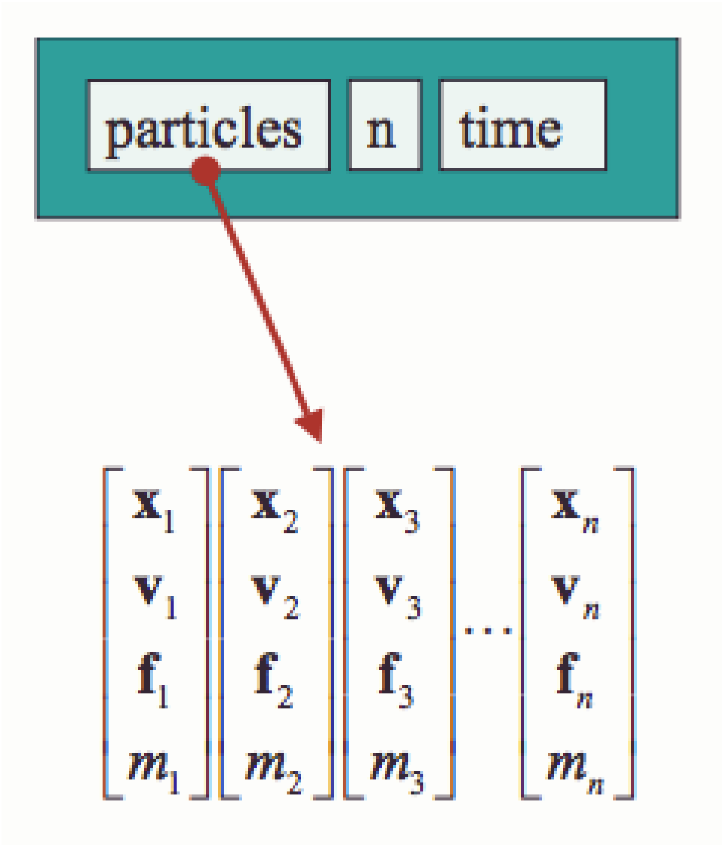


Storage

single particle

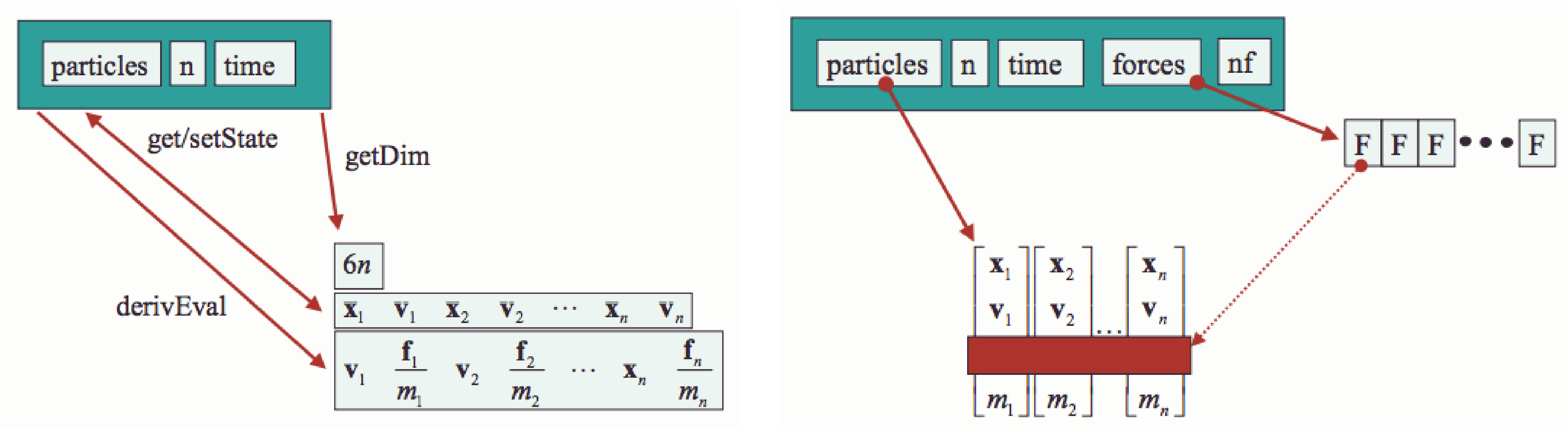


multiple particles



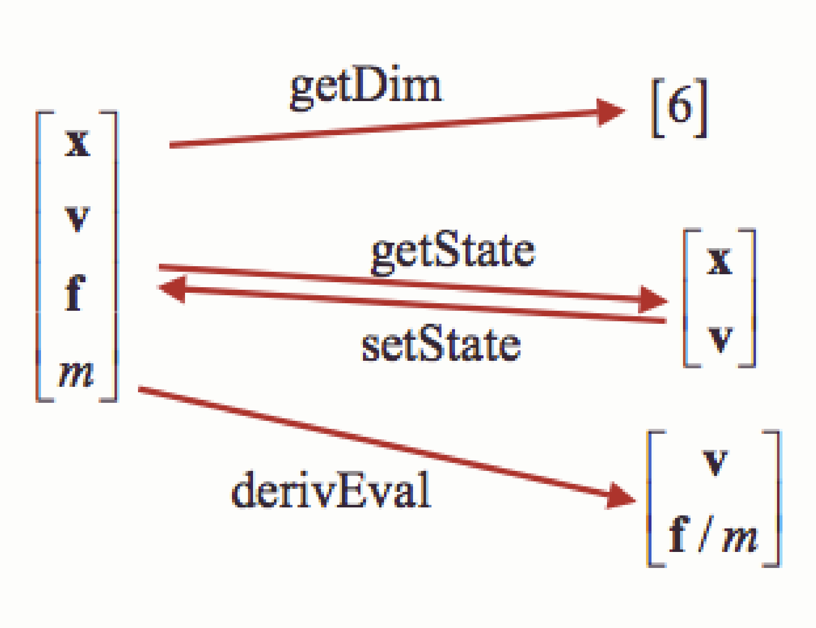
Caching

- Caching works better when cohesive memory is used for state, forces, derivatives, etc. across all particles
  - as opposed to storing each particle cohesively with all its attributes



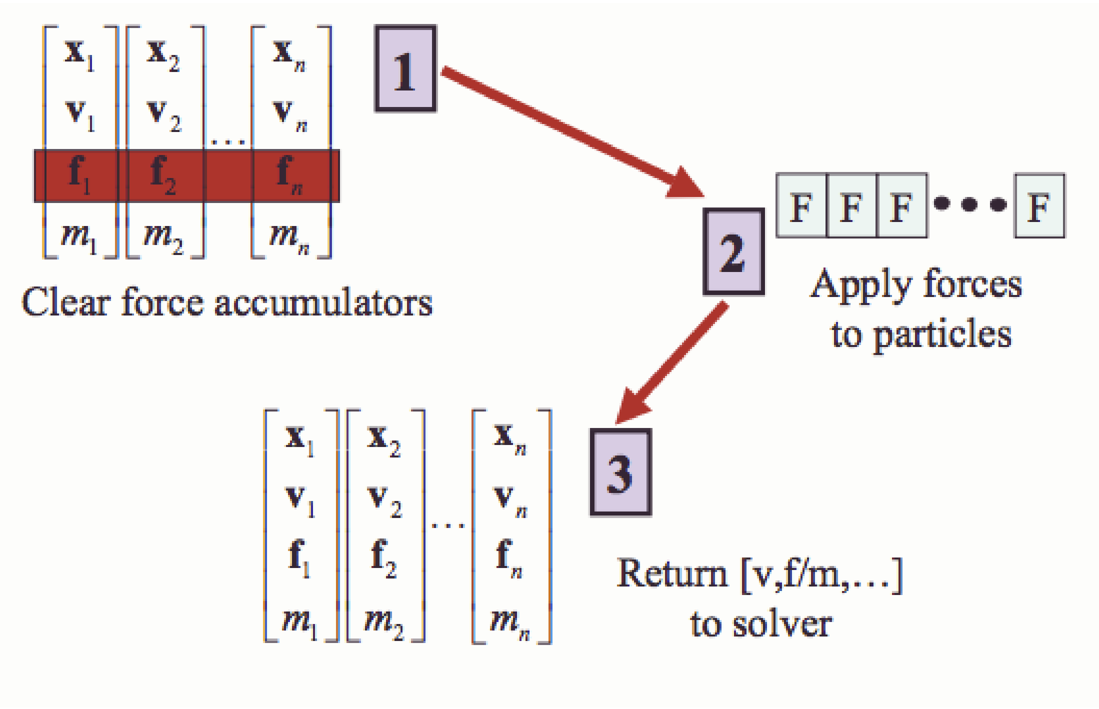
Functions

- Required functions for time integration:
  - Get the current state
  - Evaluate forces, given the current state
  - Solve the ODEs, given the forces and the state

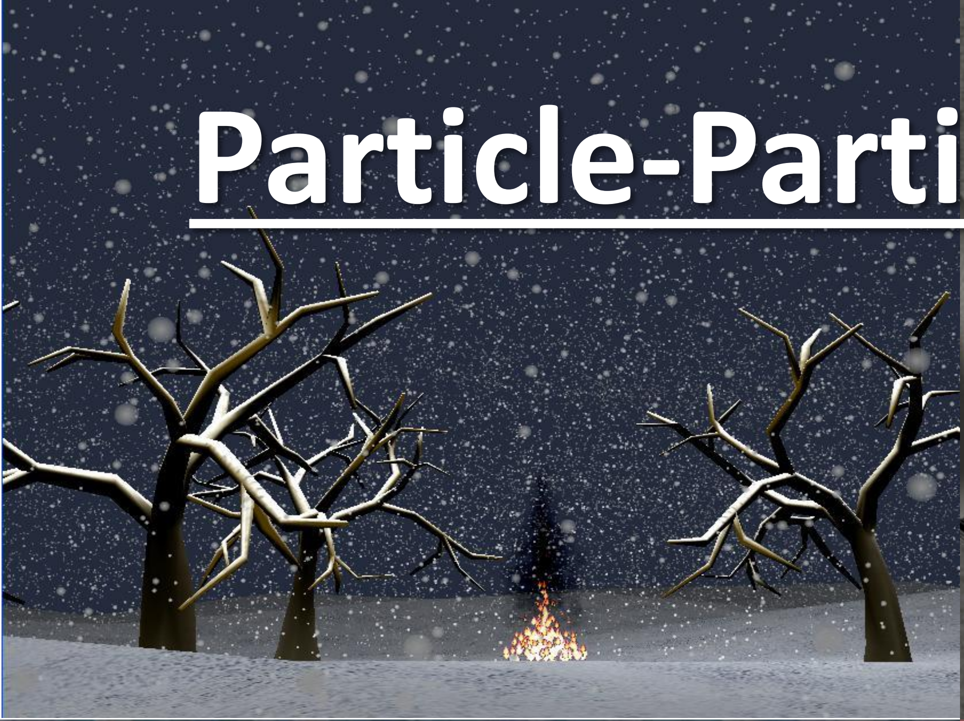


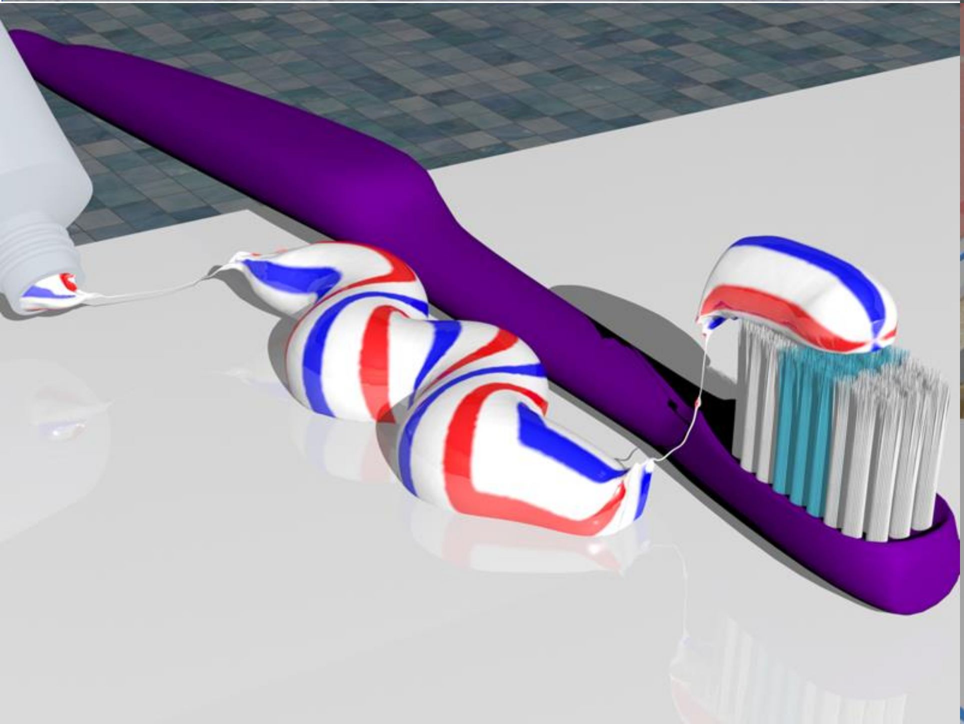
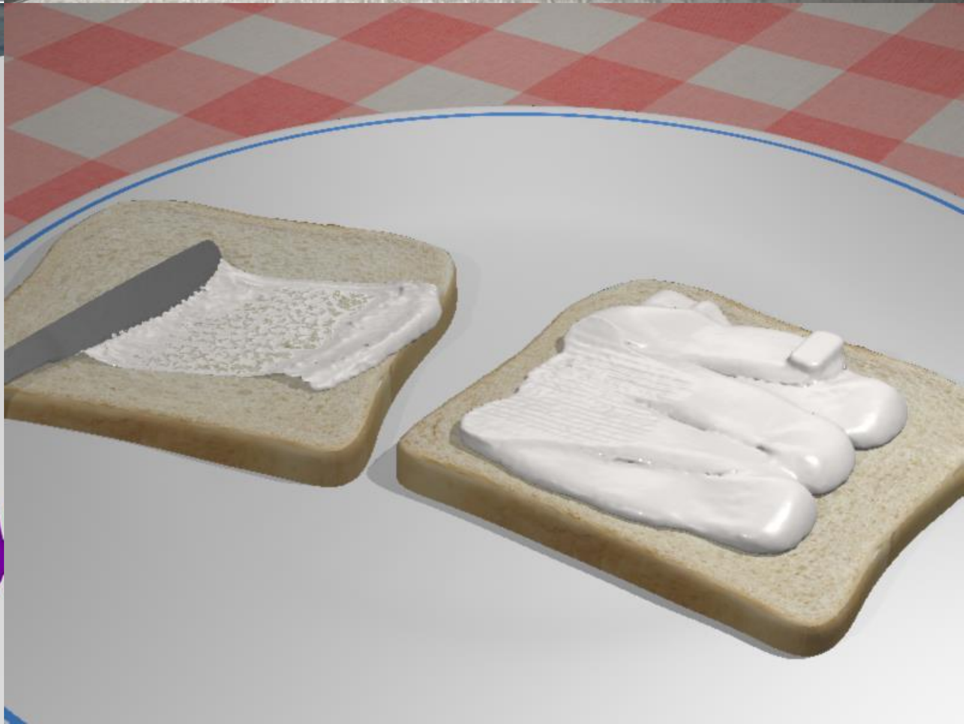
Functions

- Main Force Evaluation Loop:
  - Clear force accumulators for all particles
  - Loop over each force and evaluate it for each particle, accumulating the resulting force into the relevant particle force accumulators
  - Evaluate, **v** and **f**/m, and use them to update the ODEs for each particle



Particle-Particle Collisions



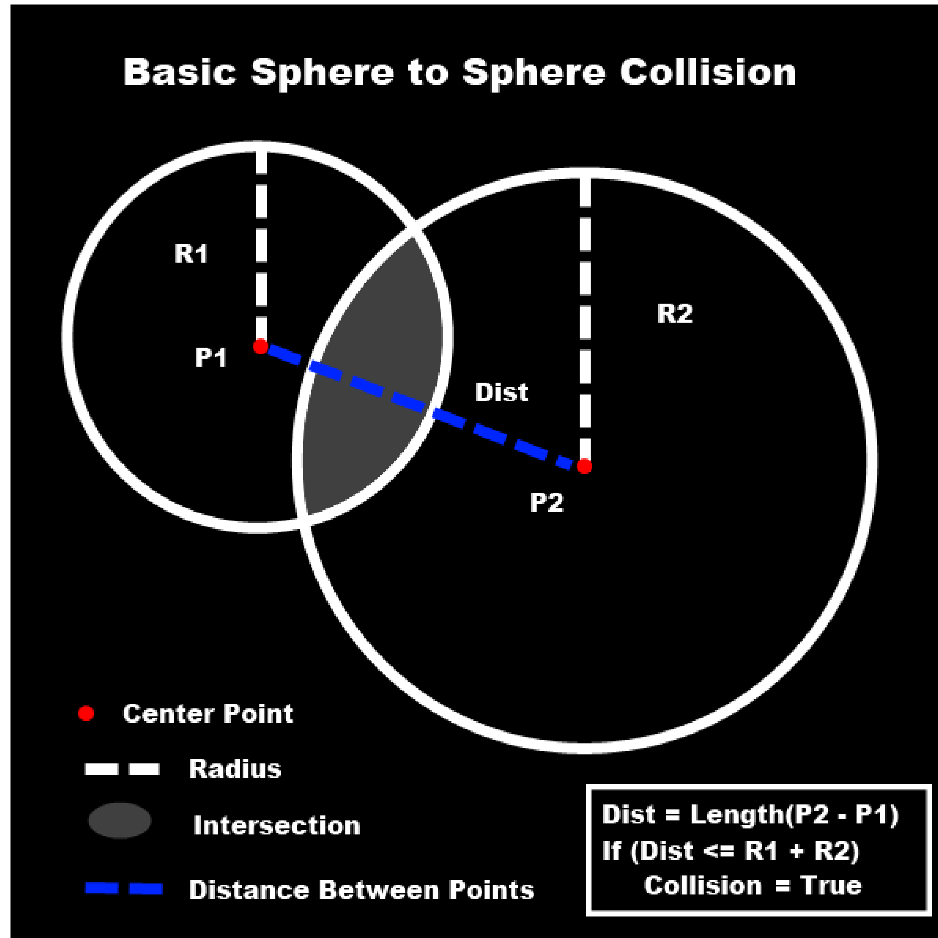



Inter-Particle Interactions

- Collisions
  - If the particles are treated as points, then collisions are improbable
  - If they are treated as spheres, then we can detect and resolve collisions
- Other forces based on the distance between the particles
  - Attraction force for inter-particle gravitation or magnetism
  - A force aiming for constant particle density when simulating water
  - Etc.

Sphere-Sphere Collisions

- Collision Detection
  - Interpenetration occurs when the particle centers are closer than the sum of their radii



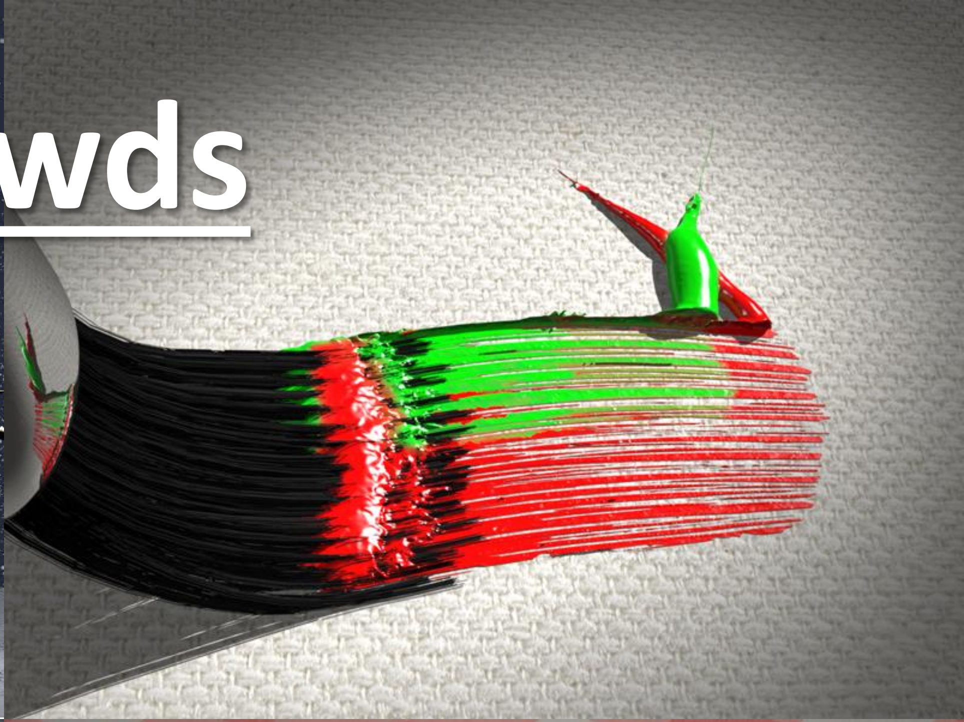
Sphere-Sphere Collisions

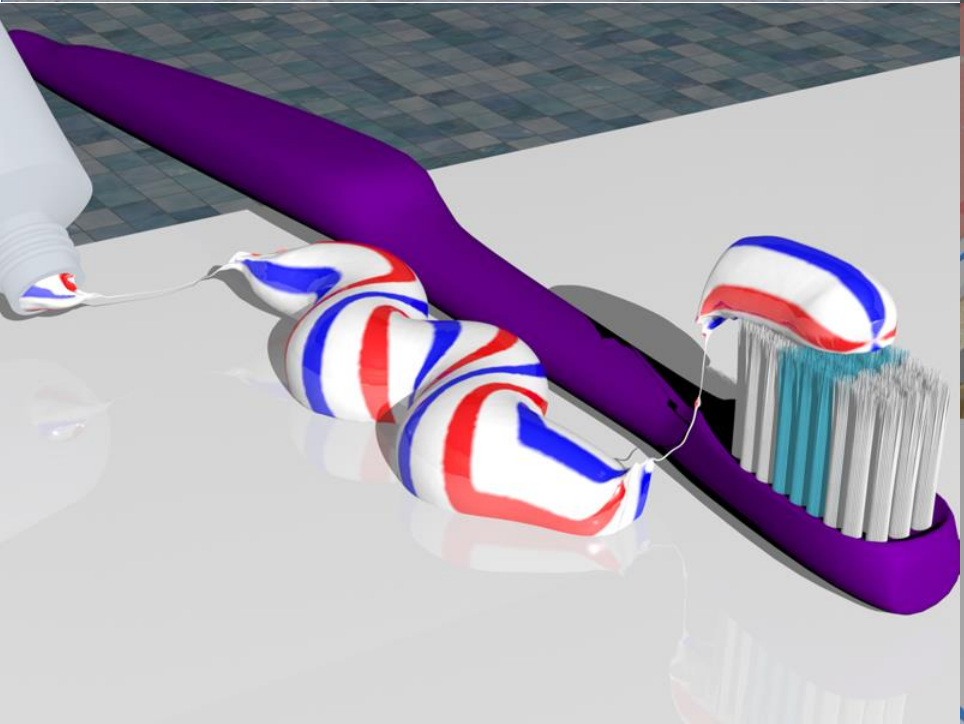
- The distance at time t^n is known
- The distance after advancing the system by Δt is also known
- Find a time t such that $t^n < t < t^n + \Delta t$ where the distance between the (center of the) spheres equals the sum of their radii
  - distance between the spheres is a linear function of time
- Perform momentum conserving collisions (last class), obtain new velocities, re-evolve the positions

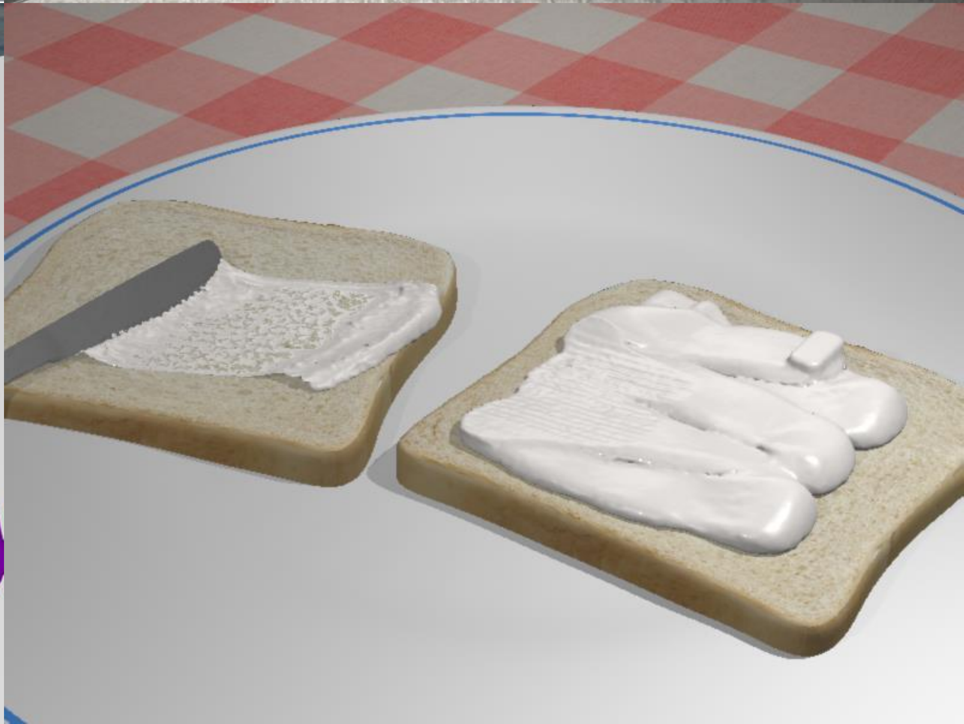
Sphere-Sphere Collisions

- If there are more than 2 spheres, taking a time step Δt can cause many spheres to collide
- Option 1: Rewind to the earliest collision, resolve it and proceed
  - Can be very slow when there are many spheres
- Option 2: Treat all collisions at once
  - iterate through them one pair at a time and add impulses
  - basically jumbling around momentum

Crowds



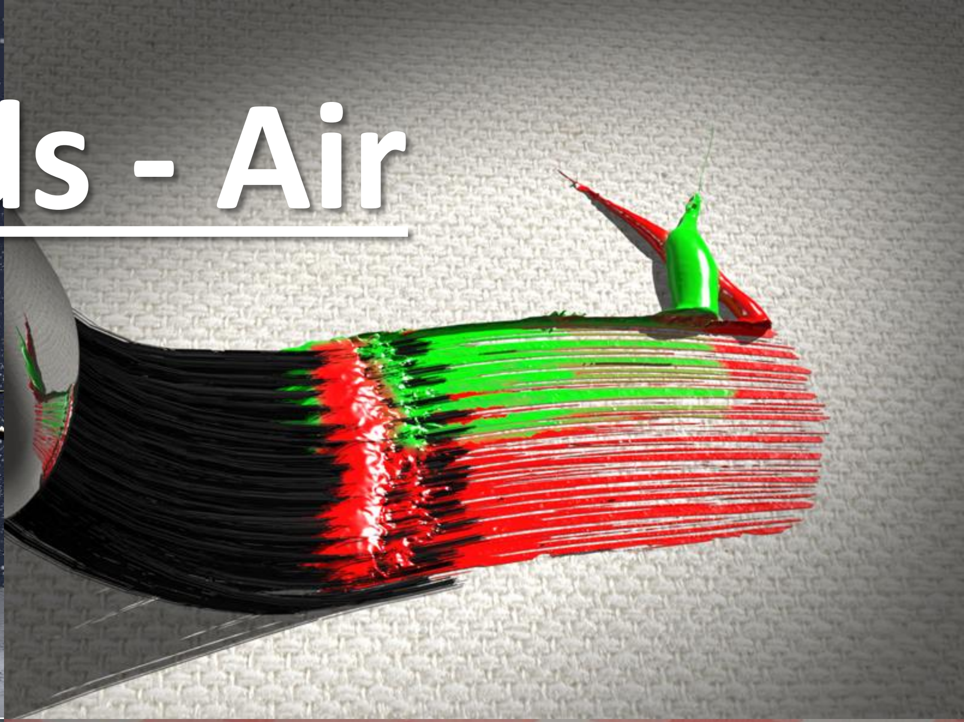


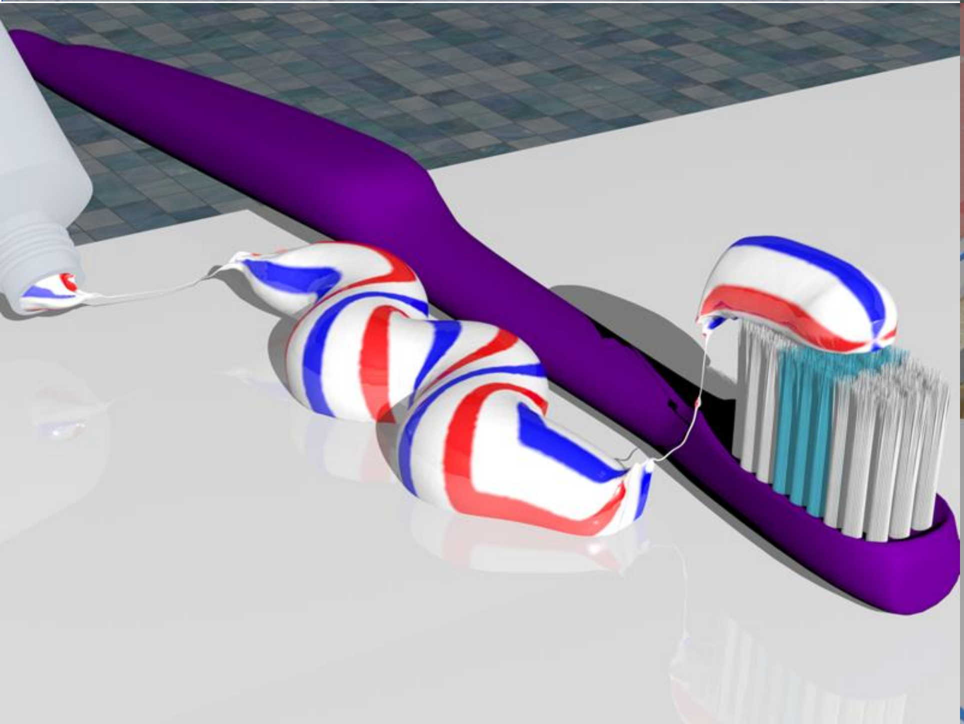


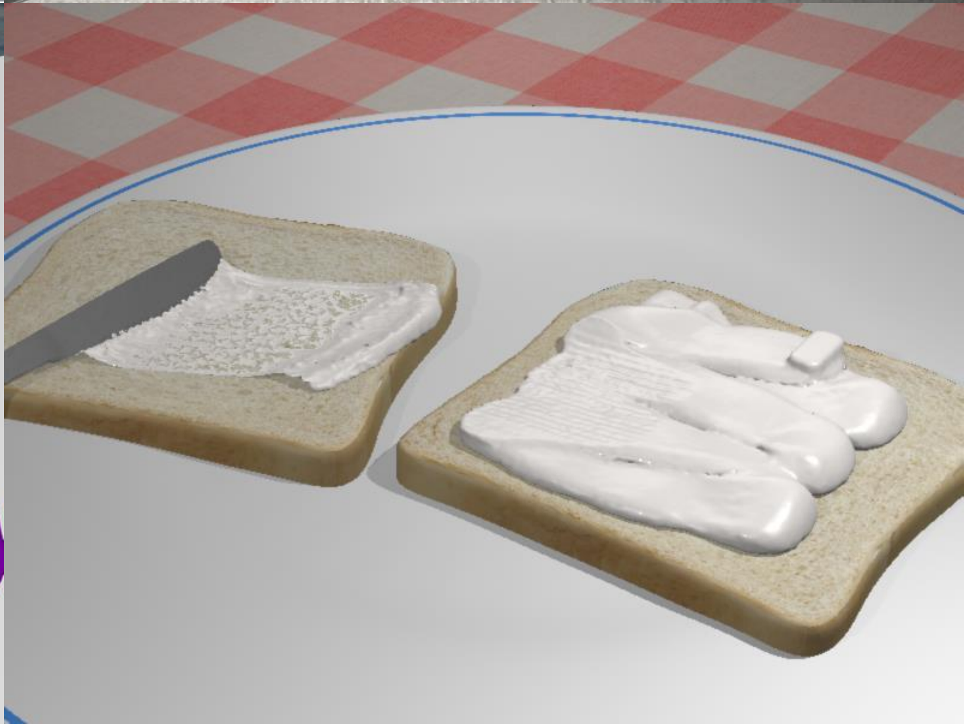
Crowds

- Particles represent agents or creatures
  - Flocks or herds of creatures
  - Pedestrians on a street
  - Panicked people
- Model each individual and take into account other nearby agents/creatures
- Model the entire group as a whole
  - group behaviors

Crowds - Air

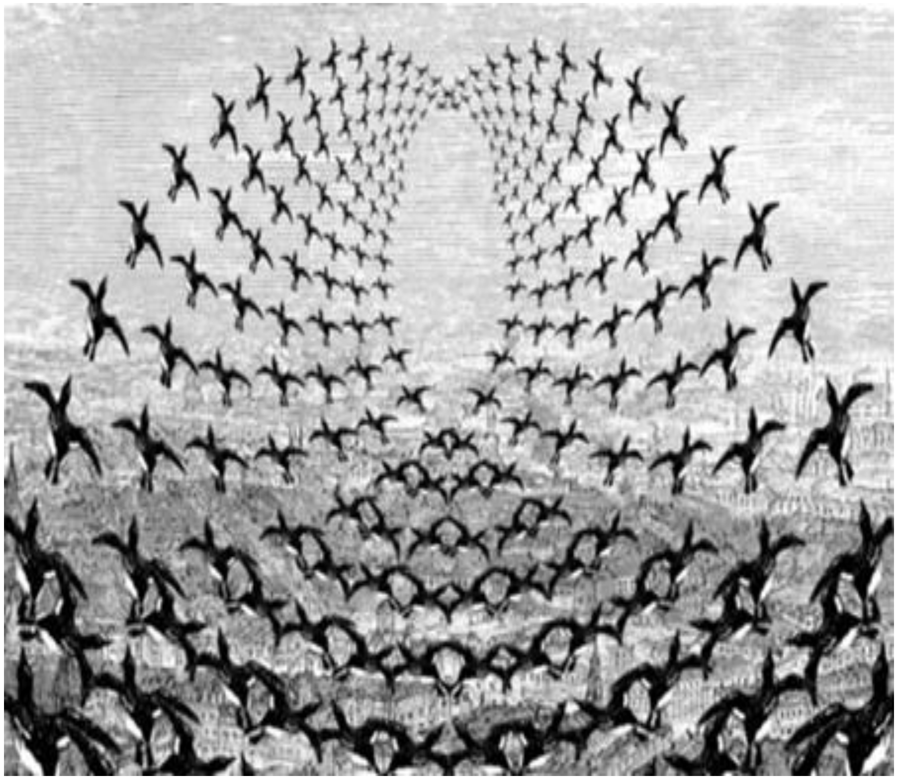






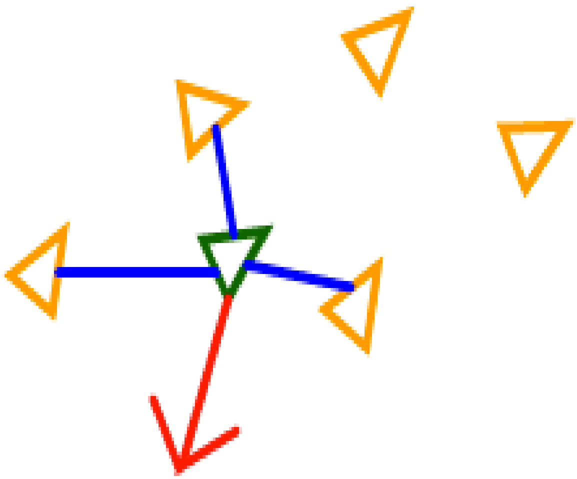
Flocking Model

- Forces are applied to each agent
  - Separation
  - Alignment
  - Cohesion
  - Avoidance



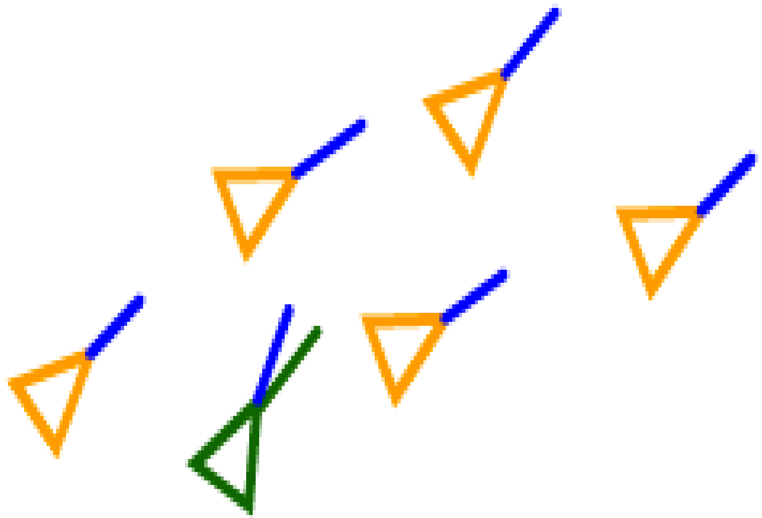
Separation

- Potential Field
- Apply a force to make sure agents don't get too close to each other
- Use visibility to limit influences



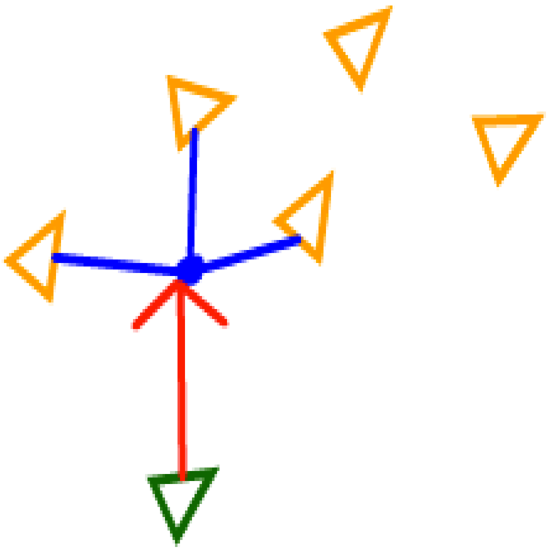
Alignment

- Try to go in the same direction as neighbors
- Go towards average velocity of neighbors



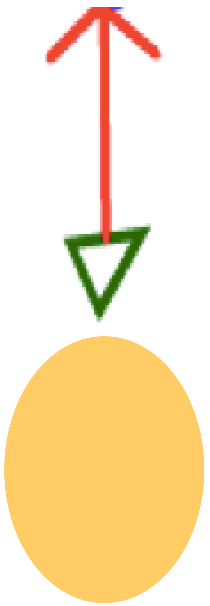
Cohesion

- Evenly space out agent with the flock
- Move position towards local average
- Keeps outliers inside the flock



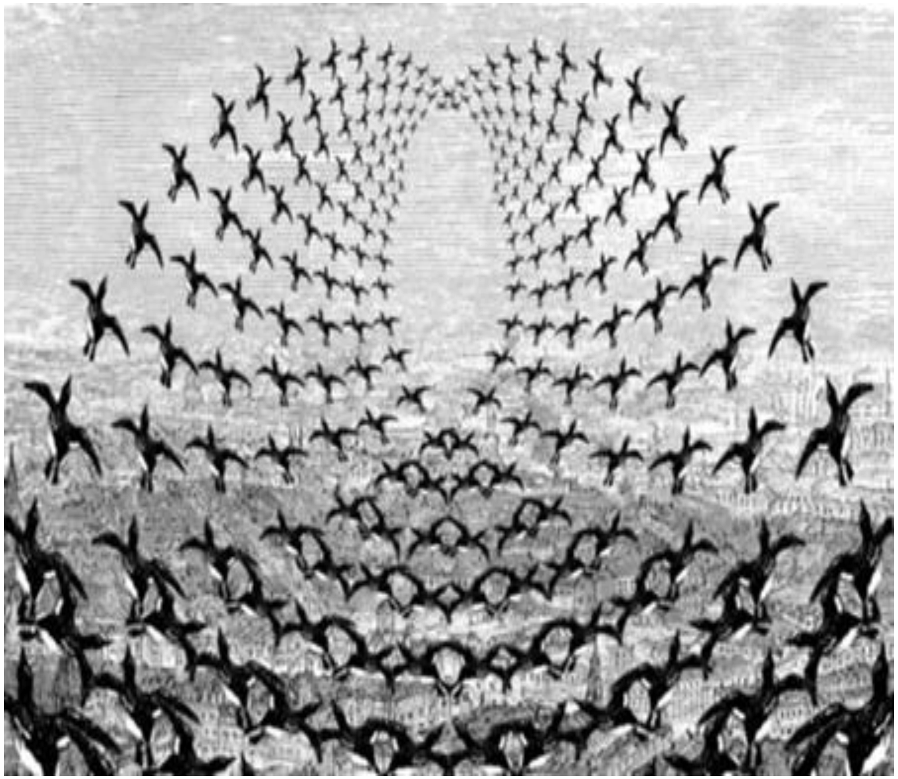
Avoidance

- Potential Field for obstacles

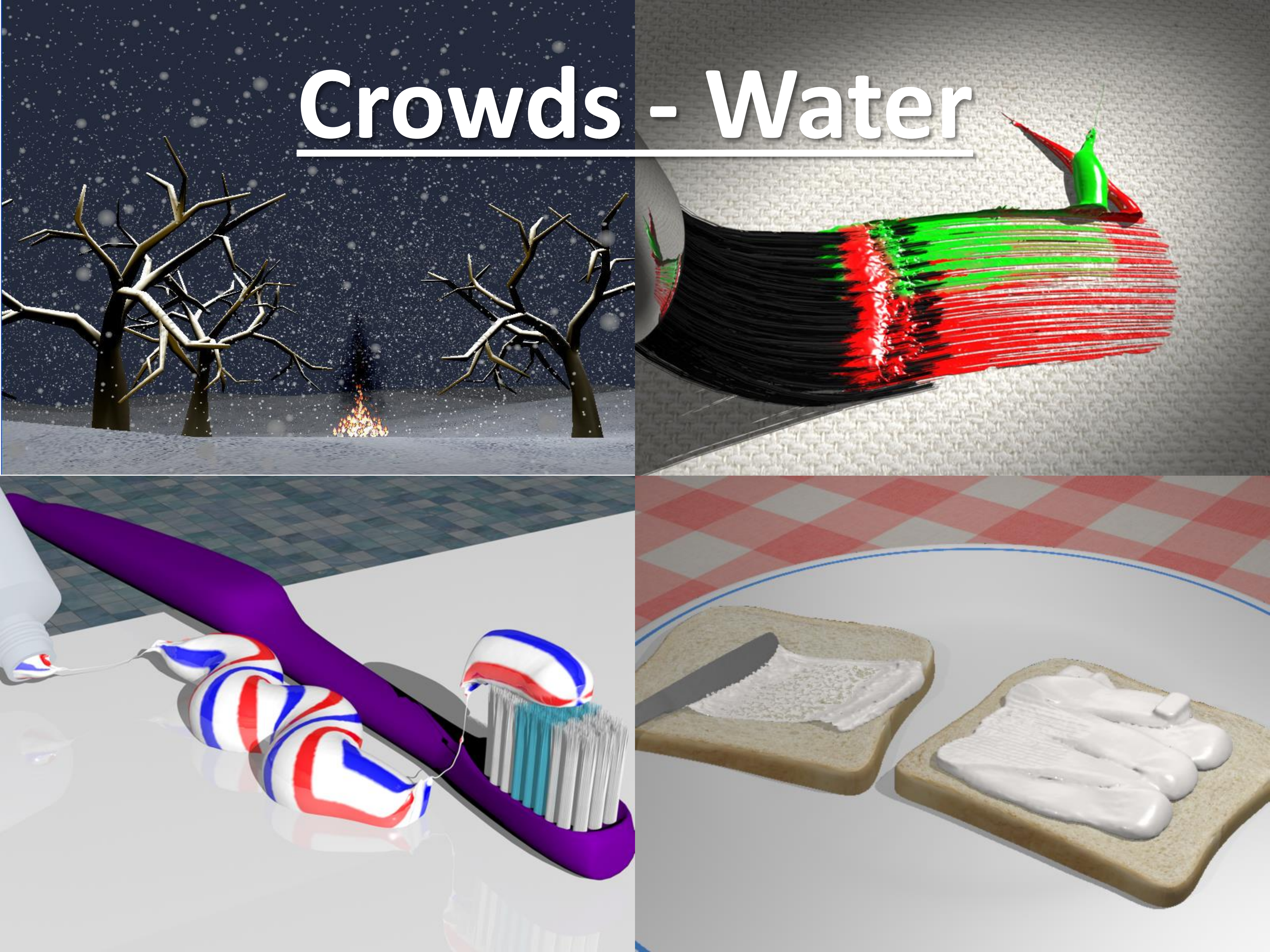


Flocking Model

- Combine all goals
  - Give a weight to each goal
  - Can also give priorities



Crowds - Water

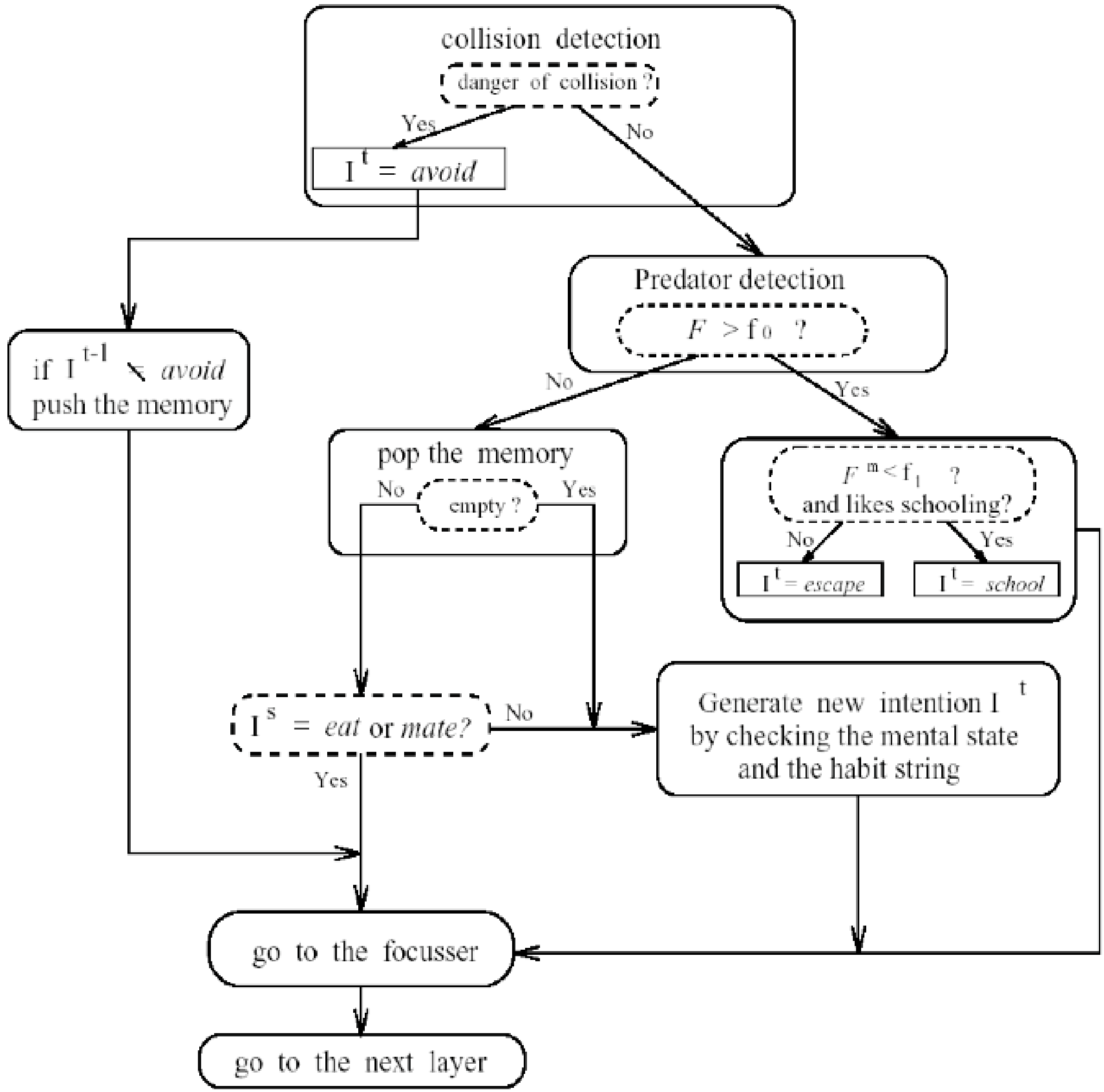


Fish

- Neutrally buoyant, but do need to keep swimming to breathe
- Can add other factors:
  - Hunger
  - Libido
  - Fear
- Add perception
  - Vision

Fish

- Each fish has a Finite State Machine which encodes complex behaviors



Question #1

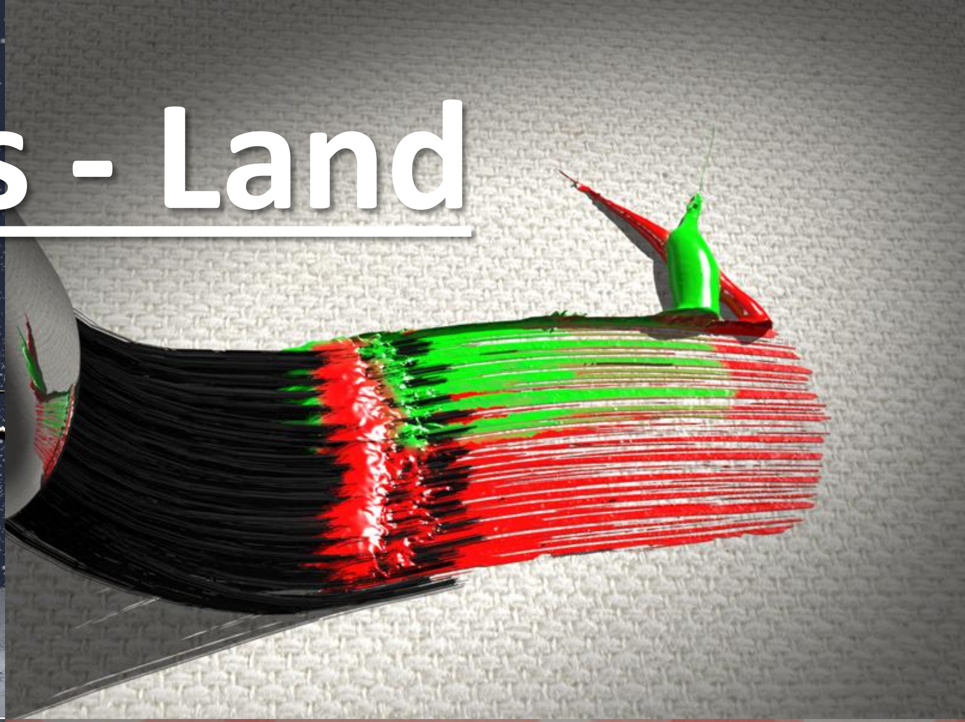
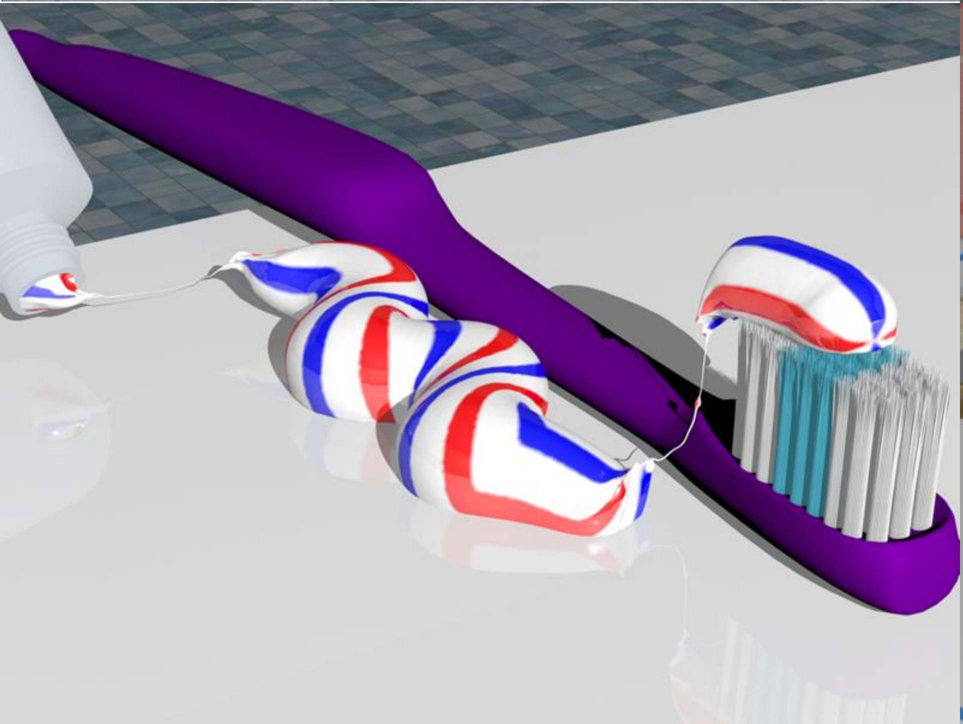
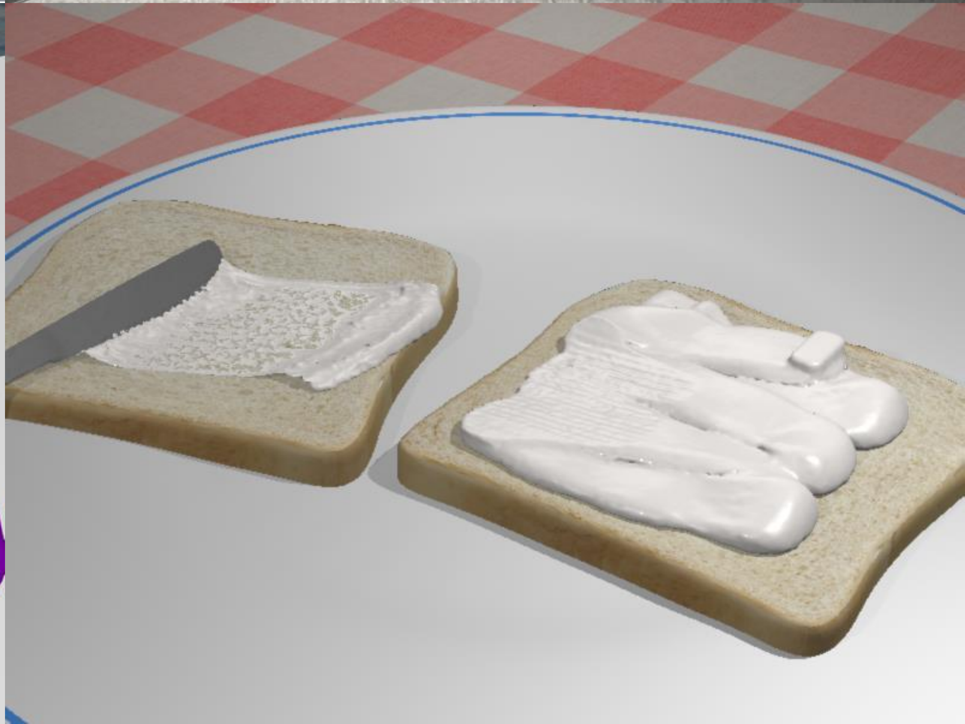
LONG FORM:

- Briefly discuss flocking models
- Answer short form question below

SHORT FORM:

- Give 5 examples flocking creatures

Crowds - Land

Humans

- Social Forces
  - Respect personal space
  - Don’t get too close to obstacles
  - Focus on motivation to act
    - What happens when you see a friend?
    - What happens when you get to a traffic crossing?

Humans

- Forces acting on an individual agent

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

Desired Motion

Social Force

Obstacle Avoidance

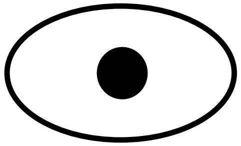
Attractive Forces

Desired Motion

- Acceleration towards a goal
  - $\vec{F}_{\alpha}^{0}(\vec{v}_{\alpha}, v_{\alpha}^{0}\vec{e}_{\alpha}) := \frac{1}{\tau_{\alpha}}(v_{\alpha}^{0}\vec{e}_{\alpha} - \vec{v}_{\alpha}).$
  - e_{α} is the desired direction
  - T_{α} is time
  - v_{α} is velocity

Social Force

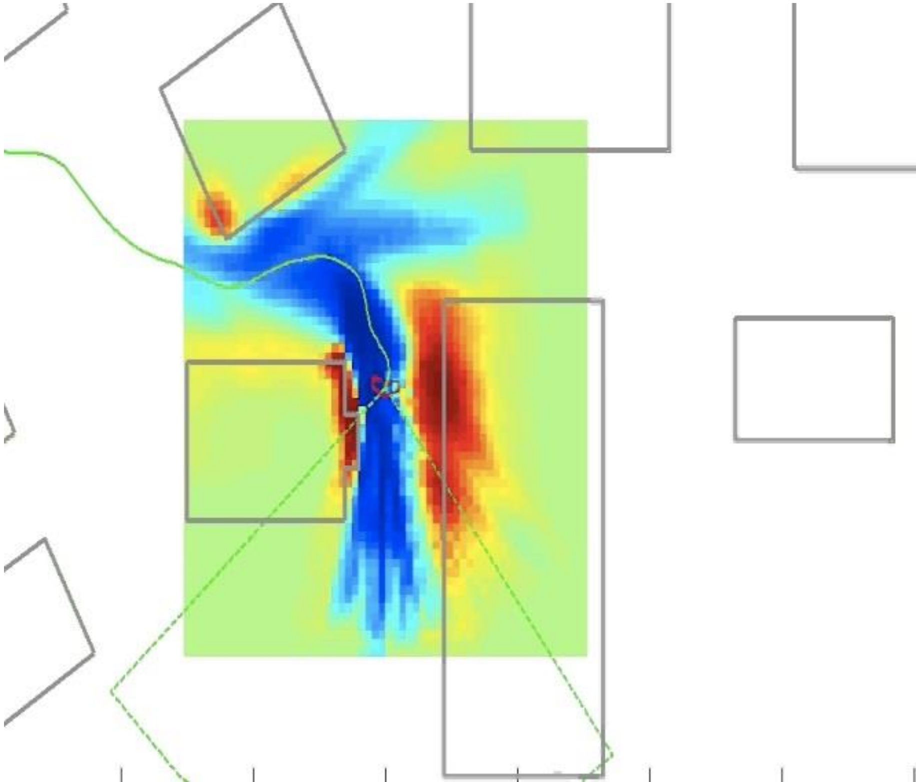
- Pedestrians keep a distance that depends on density and speed
- Implemented as a repulsive force in an elliptical shape



  - Allows agent to leave room for future actions
  - Pedestrians have limited vision so they only interact with agents that are visible
  - Forces should not be applied if there are obstacles in the way

Obstacle Avoidance

- Keep distance from obstacles
  - Similar to flocking
  - Distances vary based on obstacle type
    - Increase the strength of the potential field
    - Thicken the collision object



Attractive Forces

- Need to apply attractive forces in various social situations
  - See a friend
  - Street performers
  - Window displays
- Similar to repulsive forces but inverted
  - Can apply the same tricks to determine how much attraction

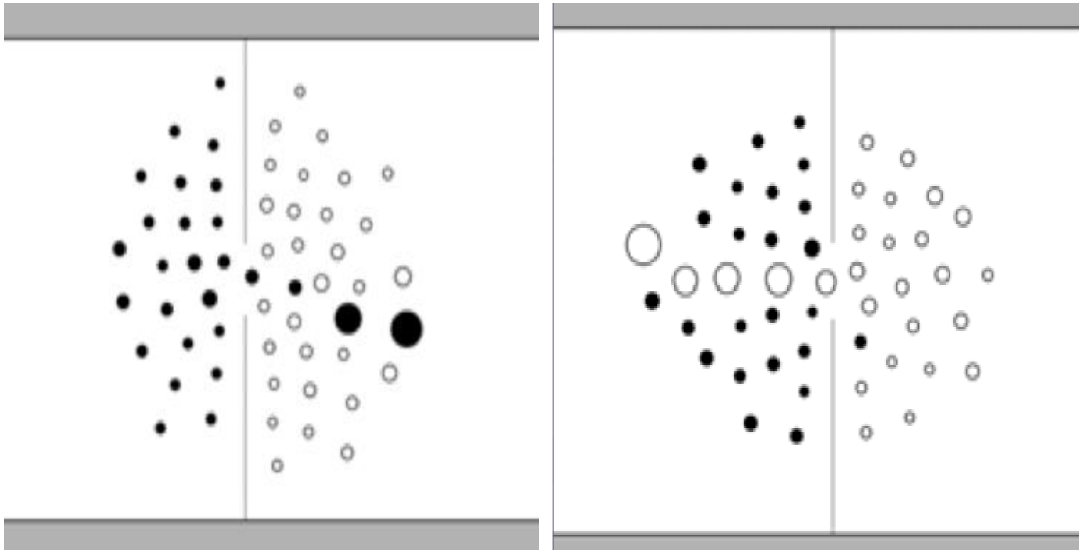
Randomness

- Add randomness to increase realism:

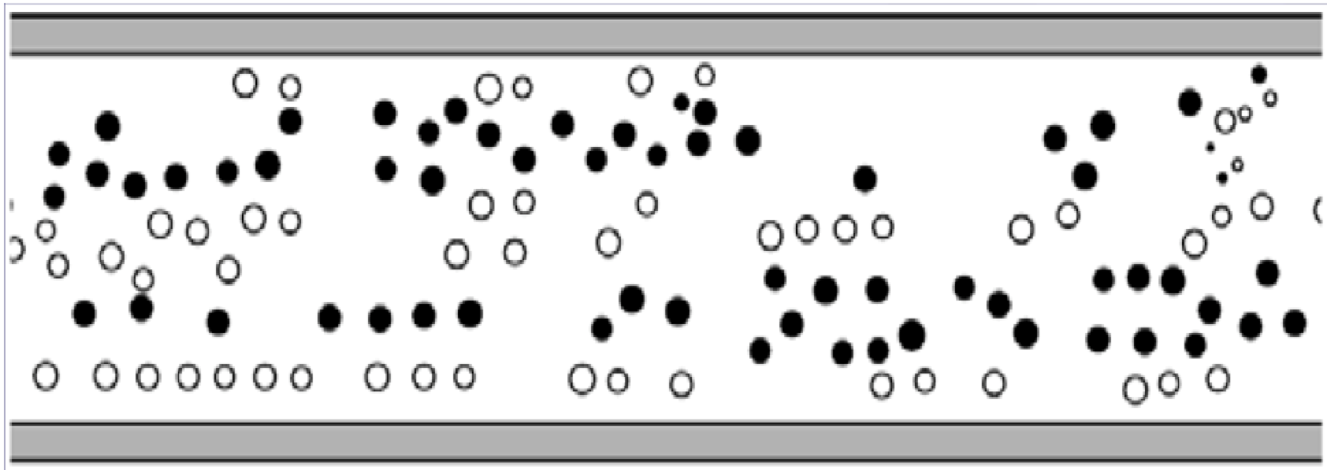
$$\vec{F}_\alpha(t) + fluctuations.$$

Emergent Behavior

- Door Oscillation

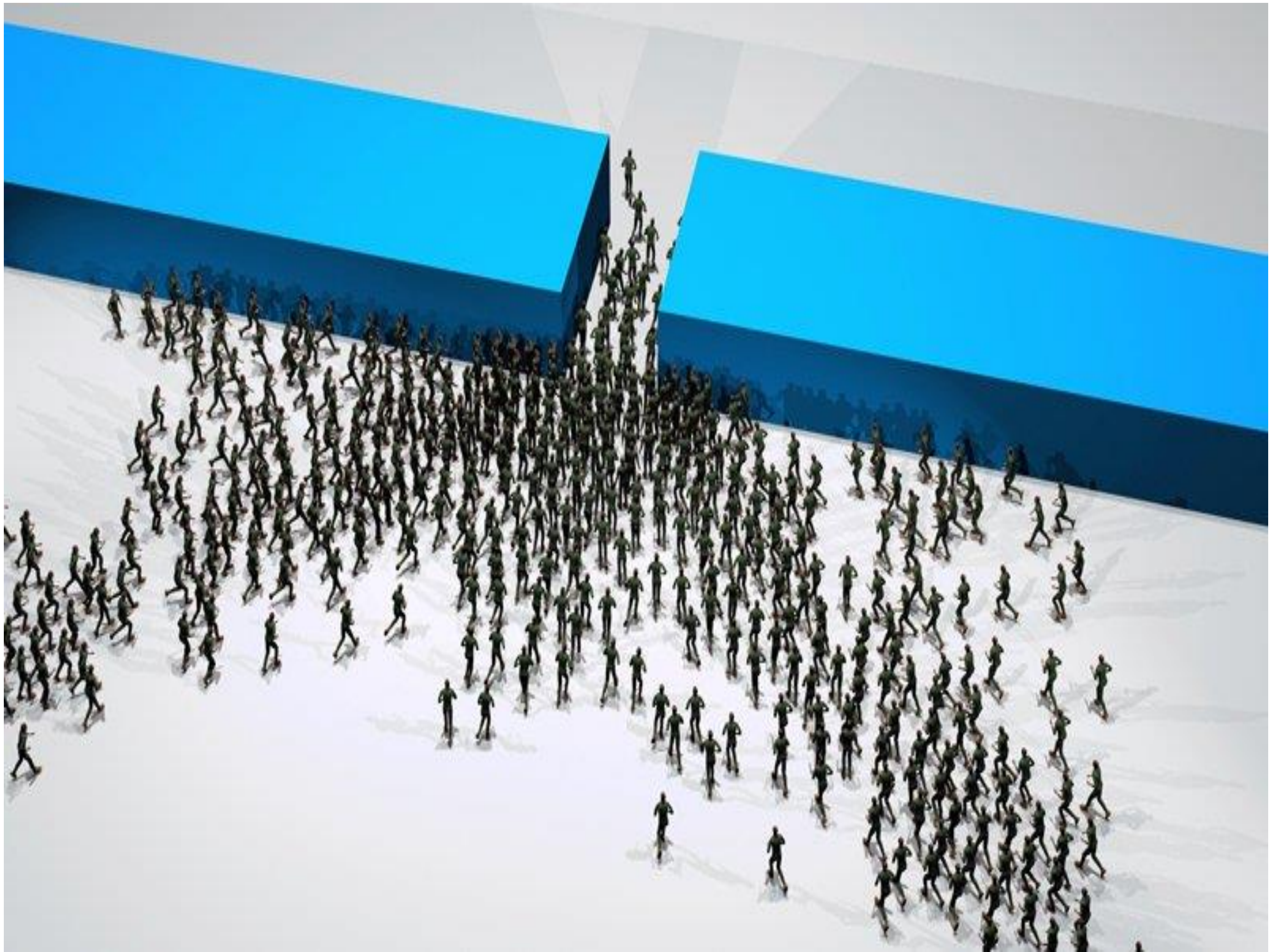


- Lane Formulation



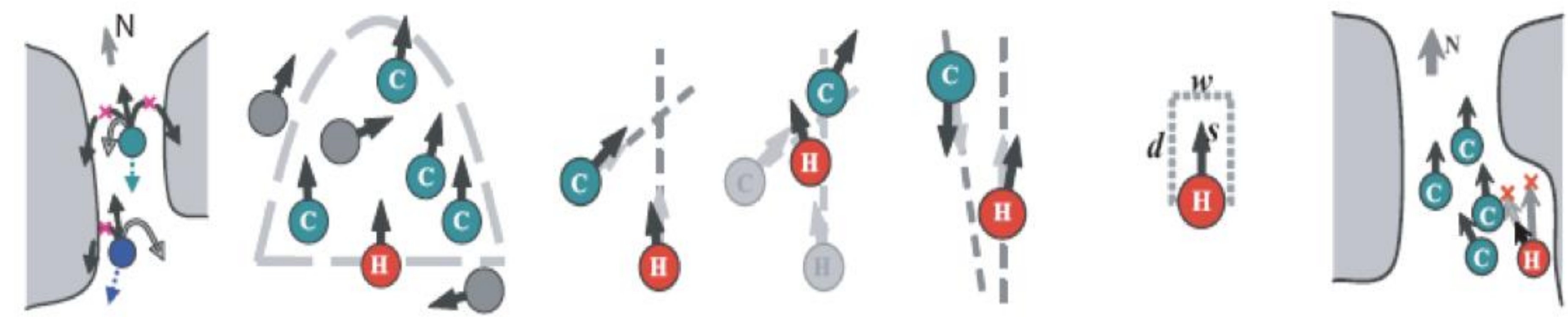
Rendering

- At render time, each dot is replaced by an articulated figure and animation walk cycles…



Collisions

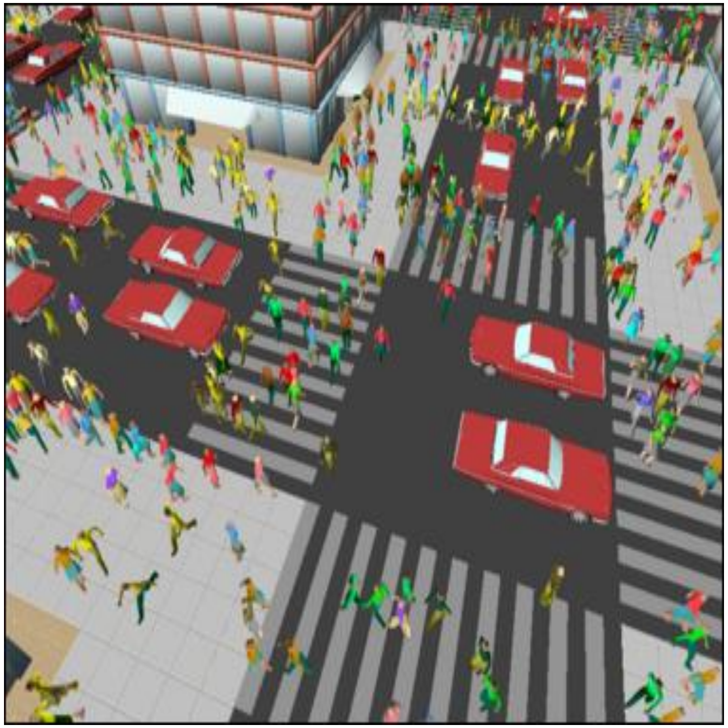
- Humans avoid each other in much more complex ways than simple potential fields can approximate
  - Wait for others to pass
  - Sidestep others



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

Collisions

- Purely local methods tend not too work well
  - there is no notion of global movement
- Need a global controller
  - global potential field that agents move through (like a fluid)



Question #2

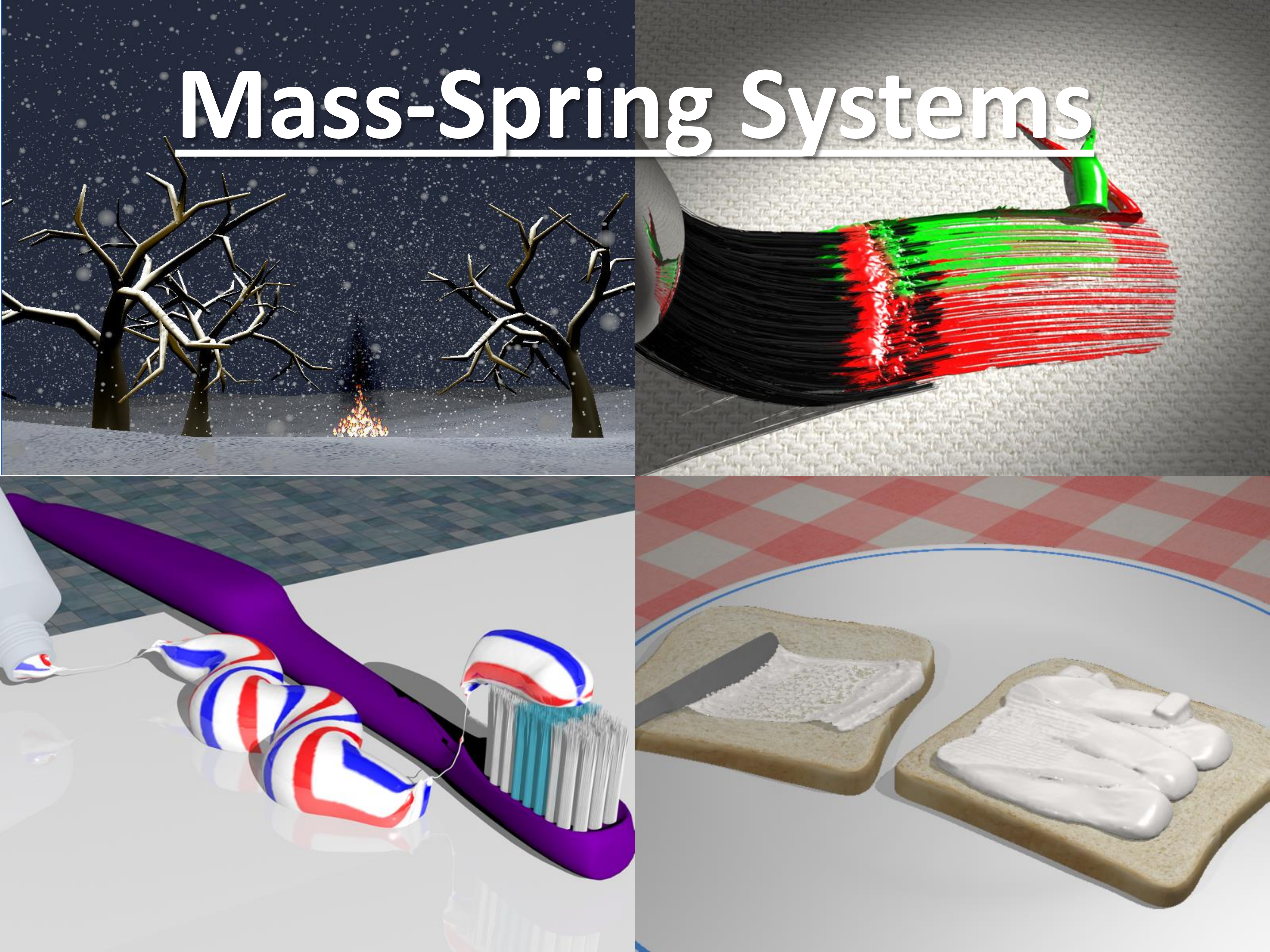
LONG FORM:

- Briefly discuss flocking for humans
- Answer short form question below

SHORT FORM:

- Describe some crowd behaviors or emergent behaviors that can be seen at an airport.

Mass-Spring Systems



Simple Spring (2 particles)

- Zero Rest Length Spring

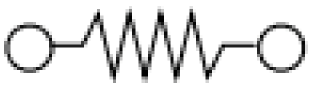
$$\boldsymbol{f}_{a\rightarrow b} = k_S(\boldsymbol{b} - \boldsymbol{a})$$

$$\boldsymbol{f}_{b\rightarrow a} = -\boldsymbol{f}_{a\rightarrow b}$$

- Force pulls points together
- Strength is proportional to the distance between points

Non-Zero Rest Length Spring

- Force is zero at the rest length
- As the spring lengthens or shortens, the spring force increases



$$\boldsymbol{f}_{a \rightarrow b} = k_s \frac{\boldsymbol{b} - \boldsymbol{a}}{||\boldsymbol{b} - \boldsymbol{a}||}(||\boldsymbol{b} - \boldsymbol{a}|| - l)$$

Rest length

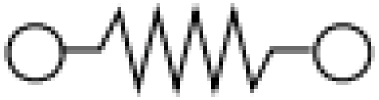
Spring Direction

Non-Zero Rest Length Spring

- Springs with zero rest length are linear
- Springs with non-zero rest length are nonlinear in multiple spatial dimensions, because of the direction term
  - in 1D this term vanishes and the spring is linear
  - Force <u>magnitude</u> is linear w/displacement from rest length
  - Force <u>direction</u> is nonlinear

Spring Damping

- Spring damping force depends on the velocity:

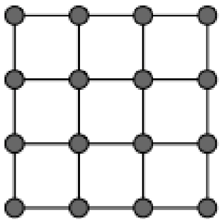


$$\boldsymbol{f}_a = -k_d \frac{\boldsymbol{b}-\boldsymbol{a}}{||\boldsymbol{b}-\boldsymbol{a}||^2}(\boldsymbol{b}-\boldsymbol{a}) \cdot (\dot{\boldsymbol{b}}-\dot{\boldsymbol{a}})$$

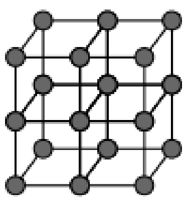
- The higher the difference in velocity, the higher the damping force
- Behaves like a drag force

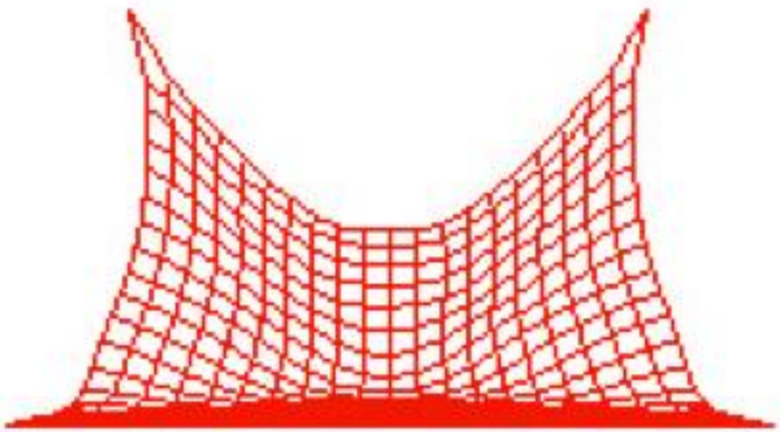
Spring Networks

- Simplest networks just connect neighboring particles
- In 2D



- In 3D

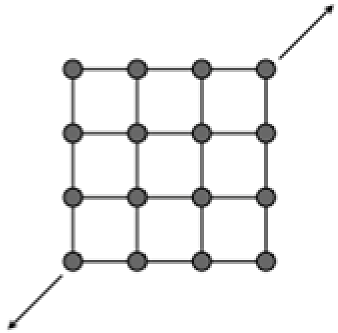




- These springs are commonly called “edge” springs

Spring Networks

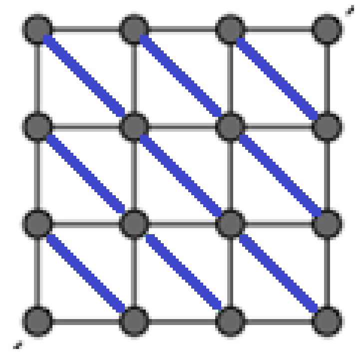
- Problems can arise from such a simple network
- Consider a 2D piece of cloth



- Provides no resistance against shearing

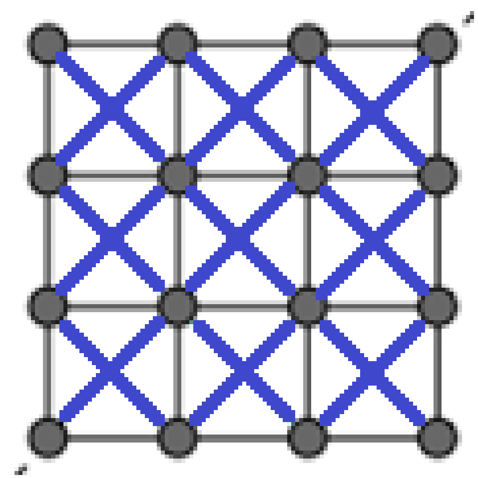
Shear Springs

- Add “shear” springs:



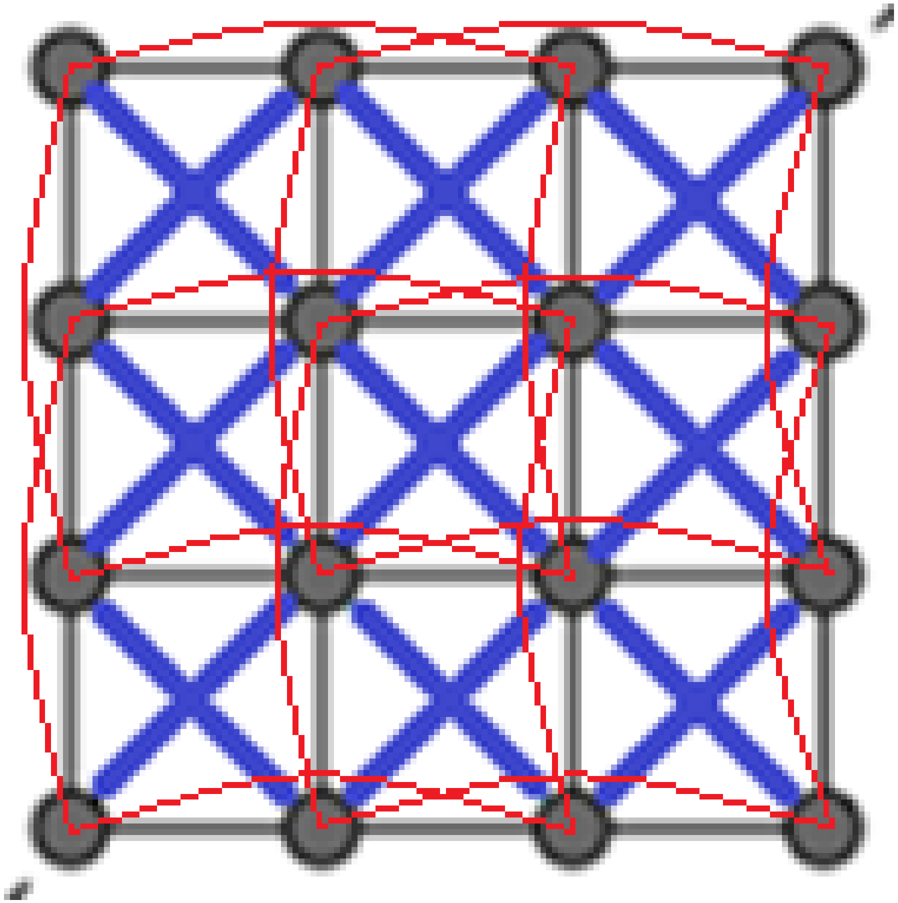
- Though these resist shearing, they behave anisotropically

- Alternatively use both directions:
- Less bias

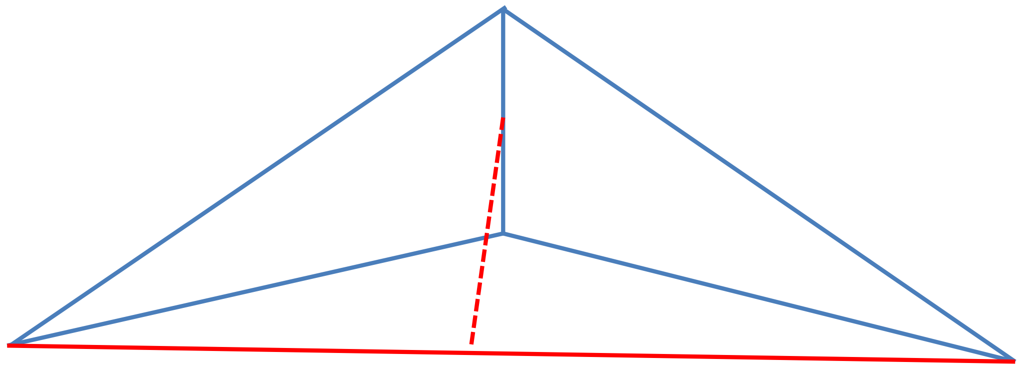


Bending Springs

- Resist out-of-plane motion, e.g. folding
- The most simple method just uses more “edge” springs
    - connecting every other point

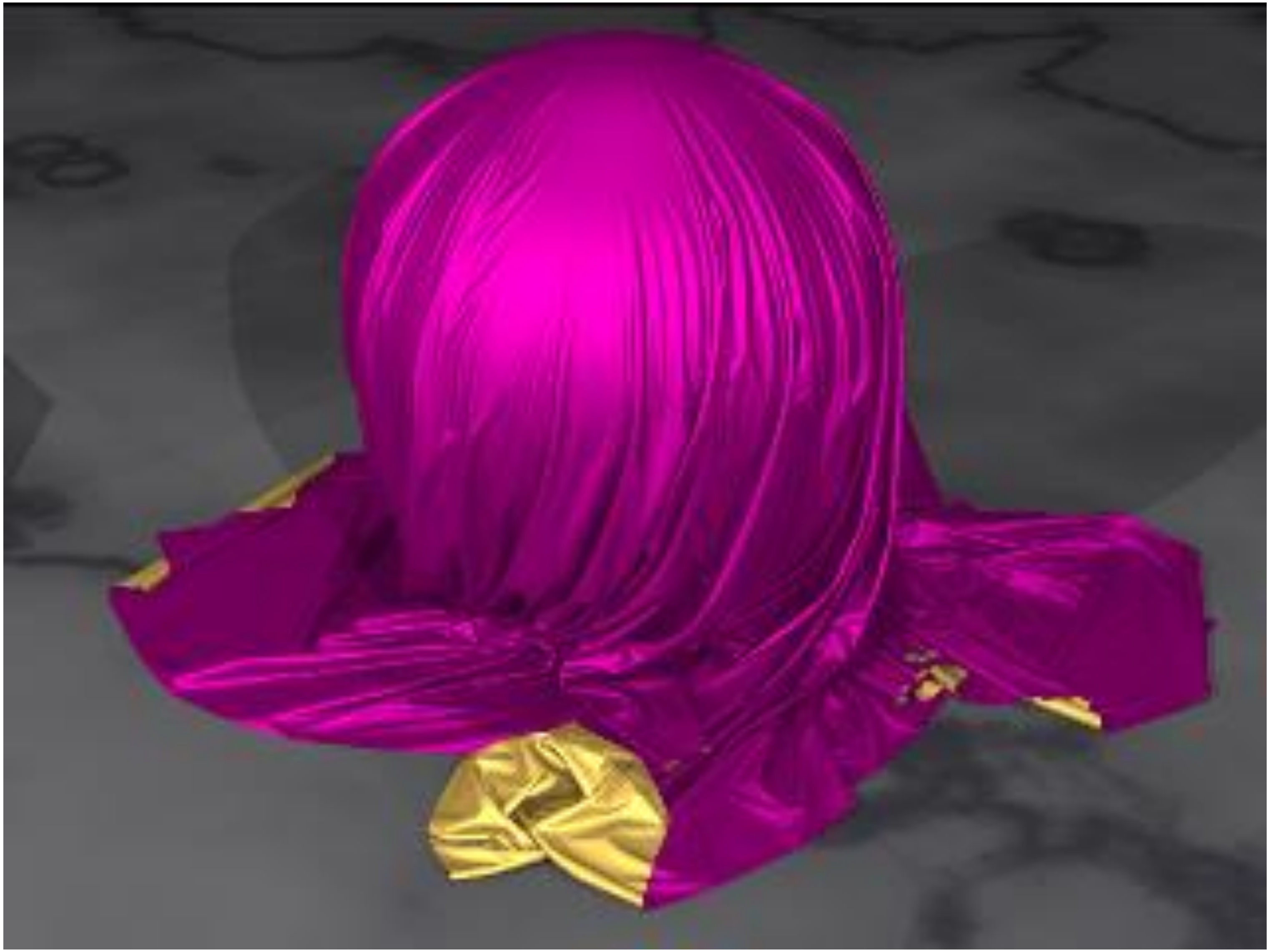


Bending Springs



- The red lines show bending springs for two adjacent triangles (blue)
- The thick red line along with the blue ones form a tetrahedron
- The thick red spring will provide almost no resistance when the two blue triangles are flat
- Hence we can add the dashed-line red spring as well.
- In general we can add springs between any pair of opposite edges or any opposite point and face

Cloth



Collision Detection

- Particle collisions with objects (see last class)
- Self-Collisions
  - Connect the particles into a triangle mesh, process collisions within the mesh
  - Two different triangles can collide in two distinct ways:
    - Point face collisions
    - Edge edge collisions
- Expensive to *detect* all possible collisions in a brute force manner
  - Use geometric acceleration structures, just as in ray tracing (see CS148)

Collision Resolution

- Repulsion forces
  - Apply repulsion forces between particles and geometry to help avoid collisions
- Impulses
  - Move particles to their next positions, detect the collisions, rewind the particles back and apply impulses that will take them to a non-colliding state
- Rigid Impact Zones
  - Cluster parts that cannot be resolved and evolve them as rigid bodies.
- Etc…

Volumetric Deformable Bodies…

- Mass-spring network
- Tetrahedra instead of triangles (make special springs for tets!)
- Collisions only need be considered for surface particles and triangles