Disclaimer: I use these notes as a guide rather than a comprehensive coverage of the topic. They are neither a substitute for attending the lectures nor for reading the assigned material.

Graphs, Search, Pathfinding

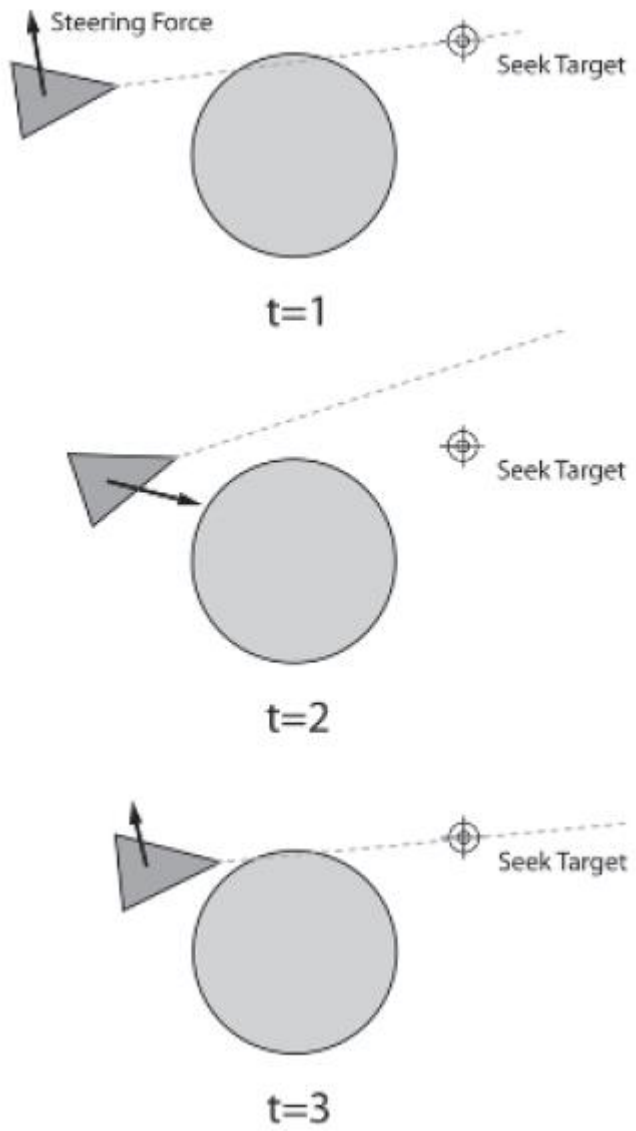
(behavior involving **where** to go)

Static, Kinematic, & Dynamic Movement; Steering, Flocking, Formations

(behavior involving **how** to go)

Announcements

- HW 3 due Sunday night, September 22
- “Judder”/”Jidder”: shaky movement when steering behaviors conflict
- Swarming:
  - https://en.wikipedia.org/wiki/Swarm_behaviour
  - Ant colony optimization lib for py:
    - https://pypi.python.org/pypi/ACO-Pants
- BSP: http://game-ai.gatech.edu/sites/default/files/documents/assignments/bsp.html



Buckland Fig 3.19

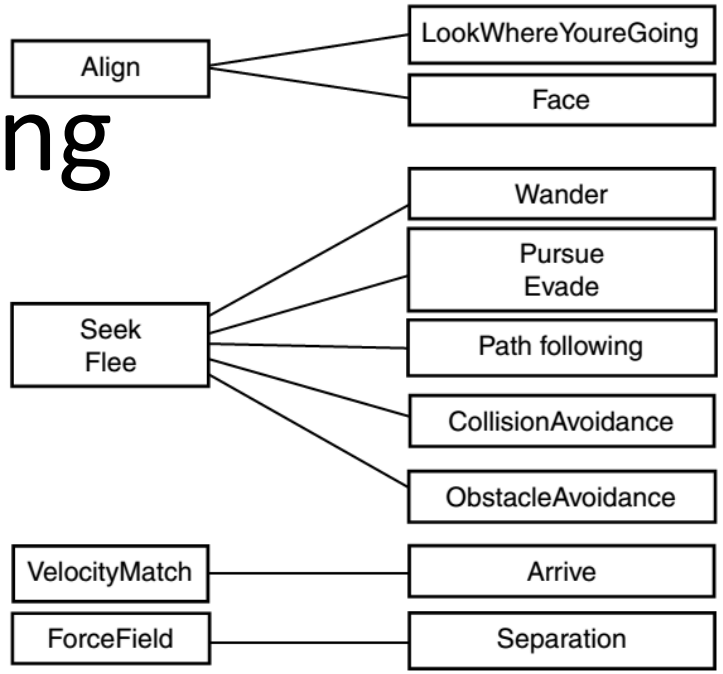
PREVIOUSLY ON…

N-2: Movement & Steering

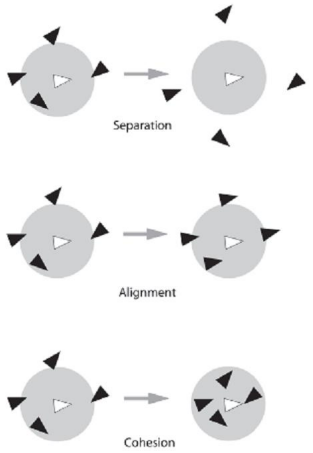
1. What do movement algorithms output in static environ?
2. What do movement algorithms input in kinematic environ?
3. What do movement algorithms output in kinematic environ?
4. What is the deal with time & variable frame rates?
5. What was the insight about updates if time << 1?
6. How are kinematic seek and pursue different?
7. What's the point of kinematic arrival?
8. Kinematic wander varies what randomly?
9. What’s the main difference between kinematic and steering/dynamic movement?

N-2, 1: Flocking, Steering

1. Steering vs flocking vs swarming?
2. Steering Family Tree
3. How might we combine behaviors?
4. Can we be sure combinations work?
5. What three steering mechanisms enable flocking?
6. Spatial partitioning w/ special data structures: Why? How?



Millington Fig 3.29



Buckland Fig 3.16

Clarifications

- Two tier nav: local vs global
  - use steering on local
  - perform seek on sequence of path nodes for global
- acceleration & forces vs instant velocity changes
- avoiding obstacles while seeking: more discussion

Movement & Steering Basics

- Movement calculation often needs to interact with the “Physics” engine
  - Avoid characters walking through each other or through obstacles
- Traditional: **kinematic movement** (not dynamic)
  - Characters move (often at fixed speed) instantaneously
  - No regard to how physical objects accelerate or brake
  - Output: direction to move in (instantaneous change to velocity with magnitude)
- Newer approach: **Steering behaviors** or **dynamic movement** (Craig Reynolds) –
  - Characters accelerate and turn based on physics
  - Take current motion of character into account
  - Output: forces or accelerations that result in velocity change
  - flocking $\subset$ steering

http://www.cse.scu.edu/~tschwarz/coen266_09/PPT/Movement%20for%20Gaming.ppt

```
struct StaticState:
    position      # 2D vector
    orientation   # single float
```

```
struct StaticMovementOutput:
    position      # 2D/3D vector
    orientation   # single float
```

Kinematics

- We describe a moving character by
  - Position: 2 or 3-D vector
  - Orientation:
    - 2-dimensional unit vector given by an angle, OR a single real value between 0 and 2 π
  - **Velocity** (linear velocity): 2 or 3-D vector
  - **Rotation** (angular velocity)
    - 2-dimensional unit vector given by an angle, OR a single real value between 0 and 2 π
- Movement behaviors output
  - Velocity
  - Rotation
- Movement behaviors input STATIC data
  - Position and orientation, no velocities

struct KinematicState:

position	# 2D/3D vector
orientation	# single float
velocity	# 2D/3D vector
rotation	# single float

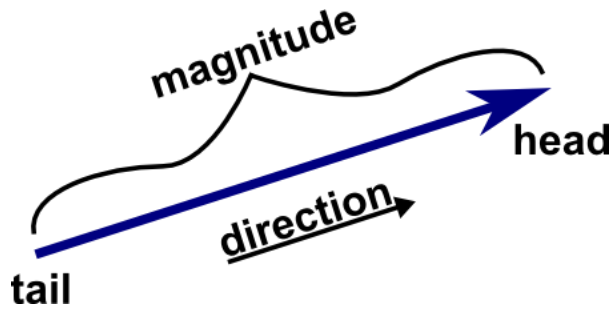
Note: rotation is angular velocity

struct **Kinematic**Output:

velocity	# 2D/3D vector
rotation	# single float rps

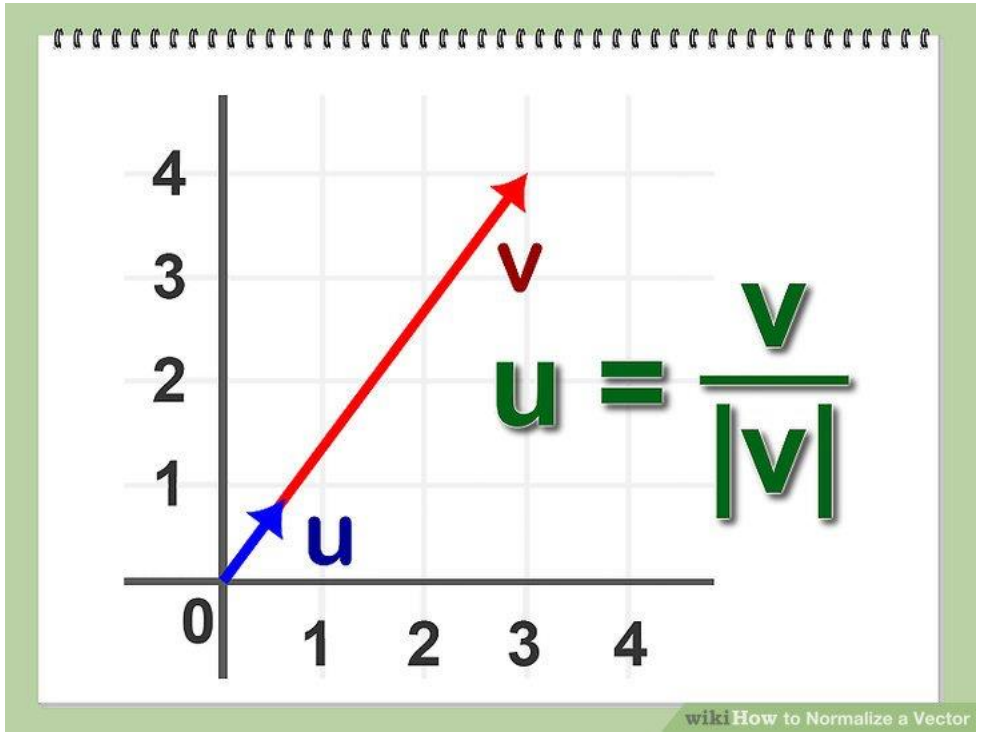
Note: Kinematic movement algorithms only input position and orientation, output desired velocity

Direction and Distance



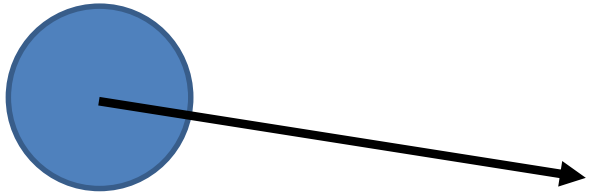
- Normalize for unit vector
- Magnitude for distance

$$\text{2D: } |\mathbf{v}| = \sqrt{x^2 + y^2}$$
$$\text{3D: } |\mathbf{v}| = \sqrt{x^2 + y^2 + z^2}$$



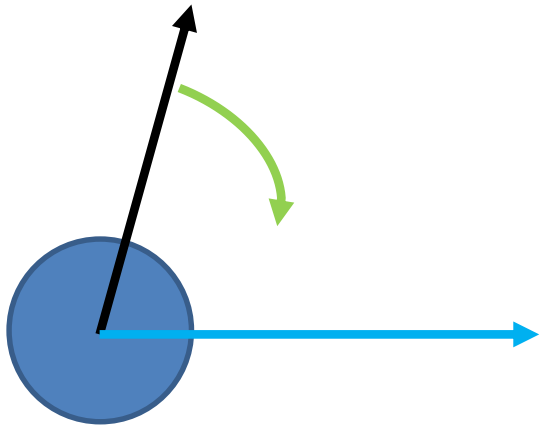
Simple Movement

- Orient agent velocity in target direction
- Very aggressive and doesn’t look very natural (can change dir instantaneously)
- Fine for discrete movement (on a grid)



Steering Movement

- Turn towards target vector
- Adjust speed, perhaps slowing forward velocity if target angle is large and accelerating to max velocity as target angle becomes small



Steering Behavior: Performance Envelope

- Typically: constant acceleration and enforced max velocity for translations and rotations (speed and turn rates)
- Can get progressively more advanced, introducing acceleration curves, separate deceleration rates, speed dependent turn rates, etc.
- Can be based on forces/torques, and agent mass

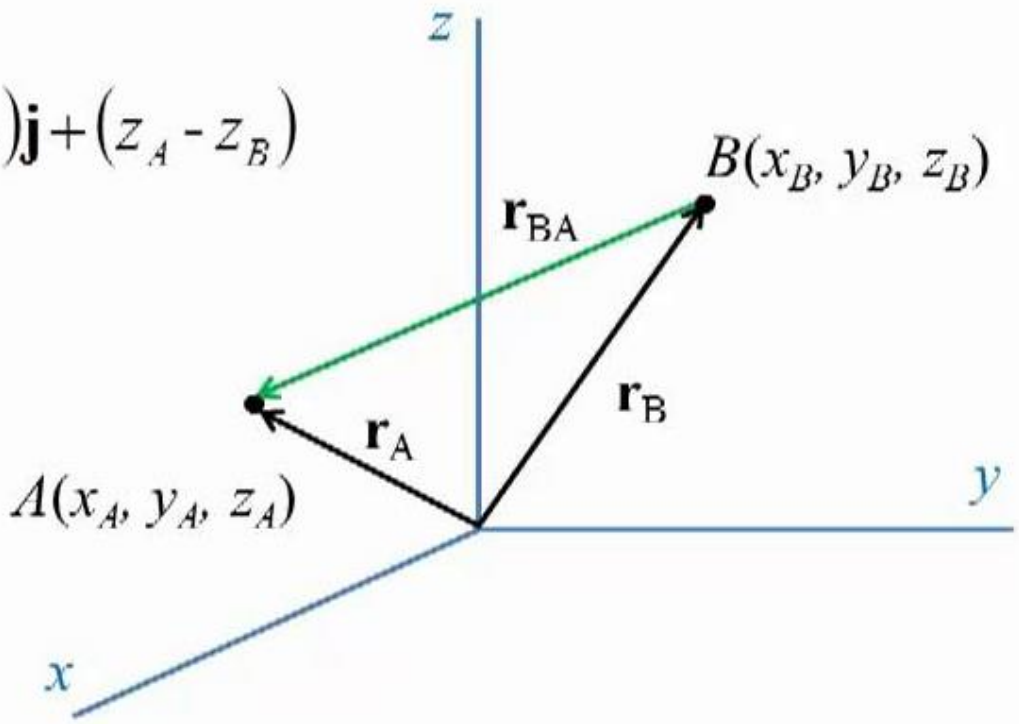
Kinematic Seek & Flee

- directs an agent toward a target position
- Input: static data of character & target
- Output: velocity in direction from *char* to *targ*
  - **velocity = target.position – character.position**
- Normalize velocity to 1 and multiply by maximum velocity
- Can ignore orientation, or update to face movement direction
- O(1) in time and memory
- Flee = -1 * velocity = character.position – target.position

Identify target

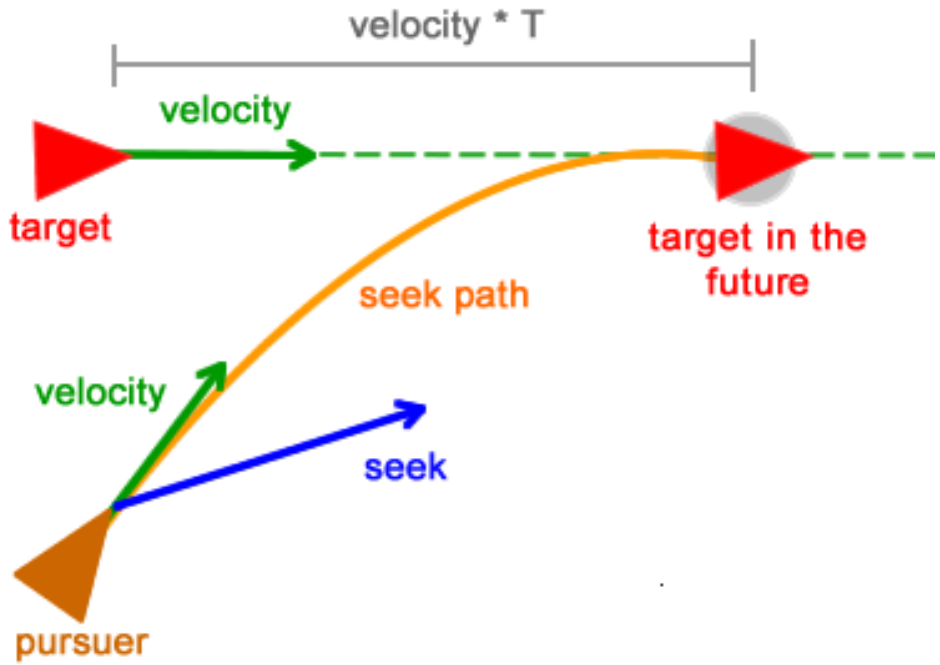
- Calculate relative position vector. A is target, B is ‘me’
  - Velocity = target.position – character.position

$$\begin{aligned}\mathbf{r}_{BA} &= \mathbf{r}_A - \mathbf{r}_B \\ &= (x_A - x_B)\mathbf{i} + (y_A - y_B)\mathbf{j} + (z_A - z_B) \\ &= -\mathbf{r}_{AB}\end{aligned}$$



Prediction (Pursue/Evade)

- No need to calculate precise intercept
  - Recalculating every frame anyways
- Dist = (target.pos – char.pos).Length()
- lookAheadT = Dist/char.maxSpeed
- **futureTarget** = target.pos + lookAheadT * target.velocity
- //Steer towards futureTarget

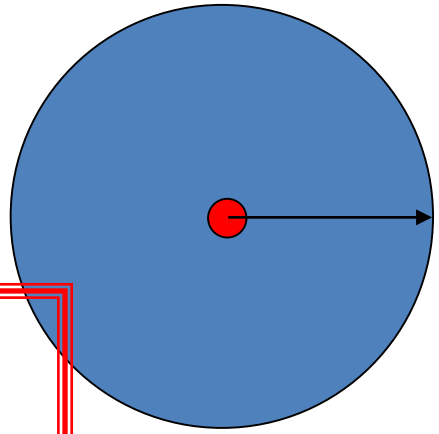


Prediction Gotchas

- Watch out for extreme predictions (very large lookahead ***t*** values)
- Could be sending your agent off the map or result in odd behavior
- Consider clamping max time prediction (and even minimum)
- Consider clipping extrapolated future positions to fit on navmesh or map, etc.

Kinematic Arrival

- Seek with full velocity leads to overshooting
  - Arrival modification: deceleration
    - Determine arrival target radius
    - Lower velocity within target for arrival



Arrival Circle:

Slow down if you get here

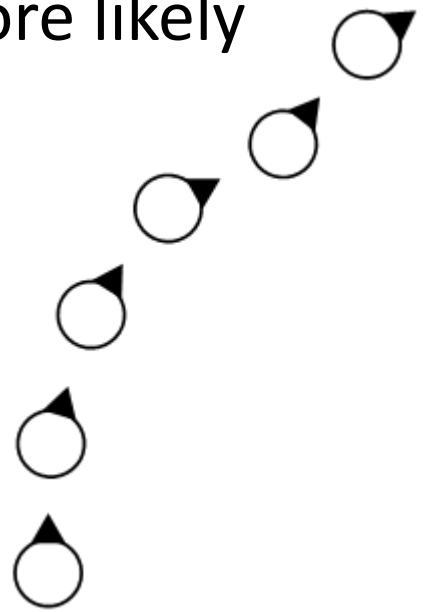
```
steering.velocity = target.position – character.position;
if(steering.velocity.length() < radius)    {
  steering.velocity /= timeToTarget;
  if(steering.velocity.length() > MAXIMUMSPEED)
    steering.velocity /= steering.velocity.length();
}
else
 steering.velocity /= steering.velocity.length();
```

Millington 3.2.1

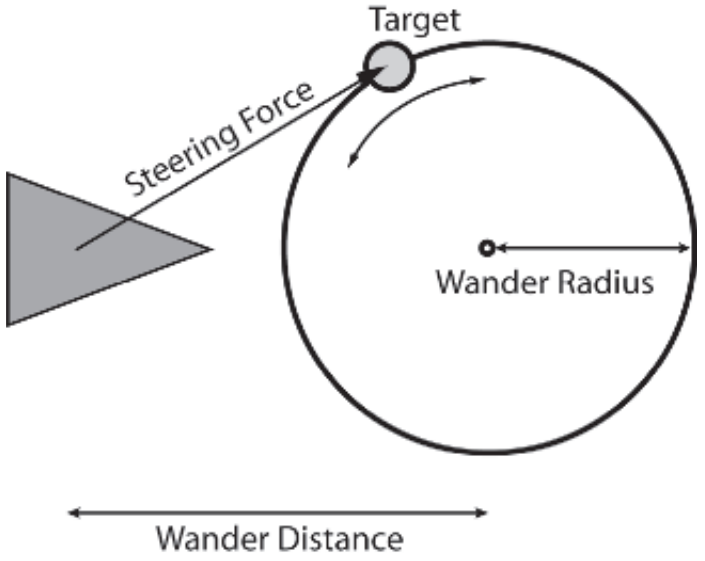
http://www.cse.scu.edu/~tschwarz/coen266_09/PPT/Movement%20for%20Gaming.ppt

Kinematic Wander

- Move in current direction at max speed
- Vary orientation by some random amount each frame
  - randomBinomial() = rand() – rand(), where rand returns [0,1]
  - random number between −1 and 1, where values around zero are more likely



Millington Fig 3.7



Buckland Fig 3.4

Steering Input Basics

- Input: agent kinematic and target info
  - Target collision info
  - Target trajectory
  - Target location
  - Average flock information
- Steering behavior doesn't attempt to do much
  - Each alg. does a single thing. Fundamental behavior "zoo"
  - Combine simple behaviors to make complex
  - No: avoid obstacles while chasing character and making detours to nearby power-ups

Dynamic/Steering Output

struct KinematicState:

```
    position        # 2D/3D vector
    orientation     # single float
    velocity        # 2D/3D vector
    rotation        # single float
```

Note: rotation is angular velocity

struct **Steering**Output:

```
    linear_acc    # 2D/3D vector
    angular_acc # single float
```

Dynamic Movement Updates

- Dynamic movement update
  - Accelerate in direction of target until maximum velocity is reached
  - (Optional) If target is close, lower velocity (Braking)
    - Negative acceleration is also limited
  - (Optional) If target is very close, stop moving

Seek + Arrive

- Dynamic movement update with Physics engine
  - Acceleration is achieved by a force
  - Vehicles etc. suffer drag, a force opposite to velocity that increases with the size of velocity
    - Limits velocity naturally

Updates to Position & Orientation

- steering.linear: a 2D vector
  - Represents changes in velocity (linear acceleration)
- steering.angular: a real value
  - Represents changes in orientation (angular acceleration)

- def update(steering, time)
  - Update at each frame (if time << 1, use Newton-Euler-1)
    - Position += Velocity * Time ~~+ 0.5 * steering.linear * time * time~~
    - Orientation += Rotation * Time ~~+ 0.5 * steering.angular * time * time~~
    - Velocity += steering.linear * Time
    - Rotation += steering.angular * Time

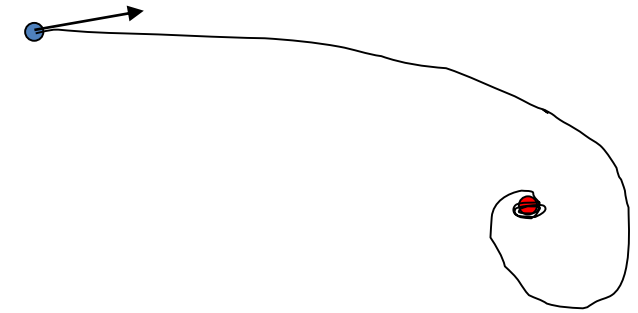
Don't forget to assign new orientation as modulo (2 π)

Don't forget to check for speeding!

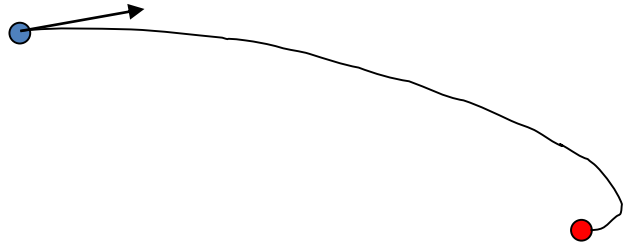
```
If Velocity.length() > maxSpeed:
    velocity.normalize()
    velocity *= maxSpeed
```

Core Steering Behaviors

- Variable Matching
  - Seek (flee): position of target
  - Align: orientation of target
  - Arrive (leave(flee)): velocity of target
  - Velocity Matching: flocking



Seek



Seek + Arrive

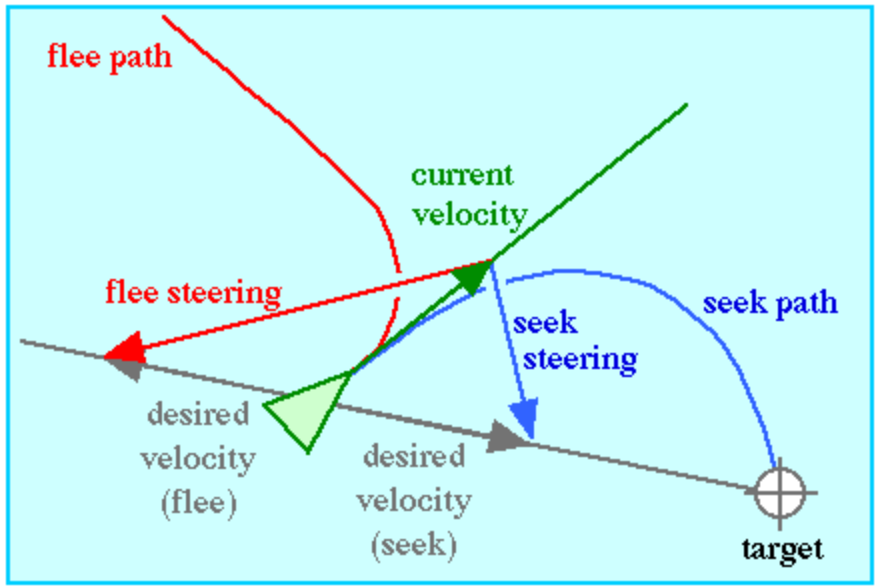
- Best way to get a feel:
  - Look at pseudo-code in Millington & Funge
  - run steering behavior program from source www.ai4g.com, https://github.com/idmillington/aicore

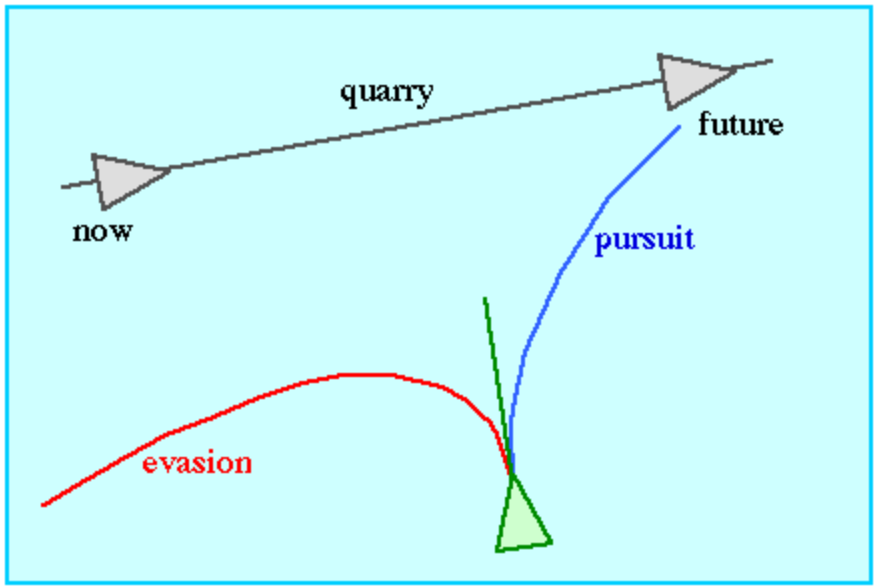
Derived & Composite Steering Behaviors

- More complex behaviors derived from core
  - Pursue (evade): Seek (flee) based on predicted target position
  - Face: Align to target orientation
  - Look where going: Face in direction of movement (using Align)
  - Collision avoidance: Flee based on obstacle proximity
  - Wander: Seek + Face some fictitious moving object

Dynamic Seek

- Seek: Match position of character with the target
- Like kinematic seek, find direction to target and go there as fast as possible
  - Kinematic outputs: velocity, rotation
  - Dynamic output: linear and angular acceleration
- Kinematic seek:
  - velocity = target.position – character.position
  - velocity = (velocity.normalize())*maxSpeed
- Dynamic seek:
  - acceleration = target.position – character.position
  - acceleration = (acceleration.normalize())*maxAcceleration





desired_velocity = normalize (position - target) * max_speed
steering = desired_velocity - velocity

http://www.red3d.com/cwr/steer/gdc99/

(static, kinematic, dynamic) Movement **Steering Continued**, Flocking, Formations

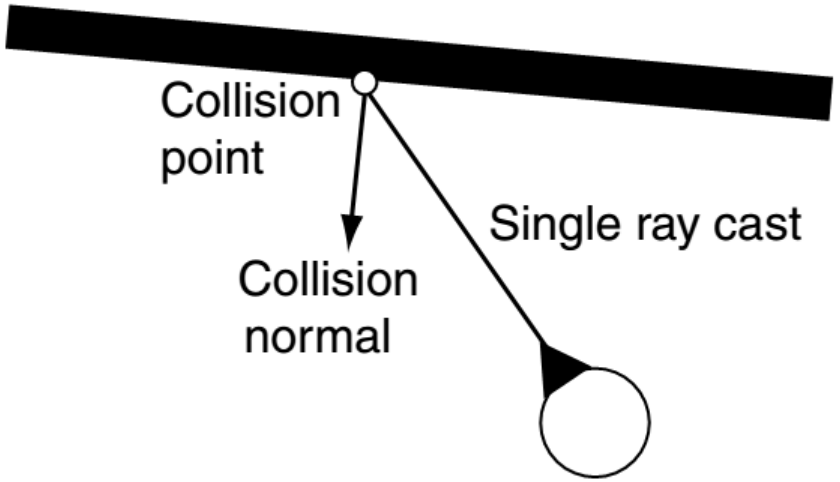
2019-09-11

M&F 3.1-3.4

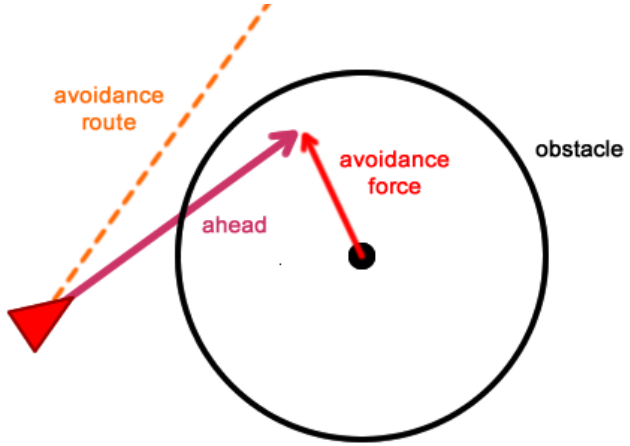
B 3

Obstacle and Wall Avoidance

- Cast one or more (distance-bounded) rays out in direction of motion
- Use collisions to create sub-target for avoidance
- Perform basic seek on sub-target
- Alternatives:
  - Avoidance force
  - Flow field

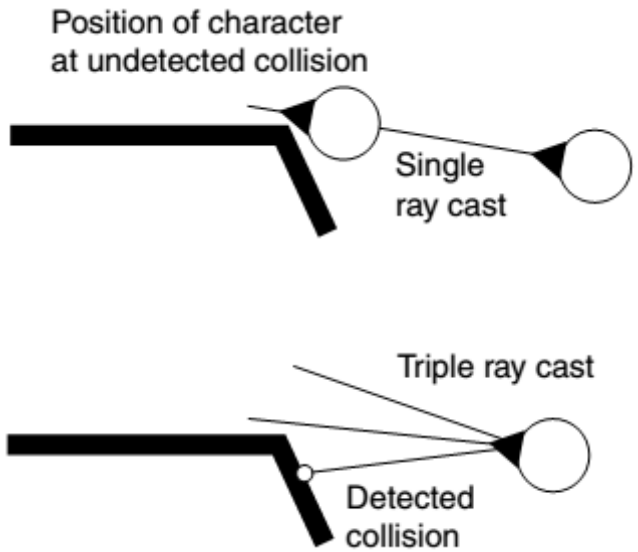


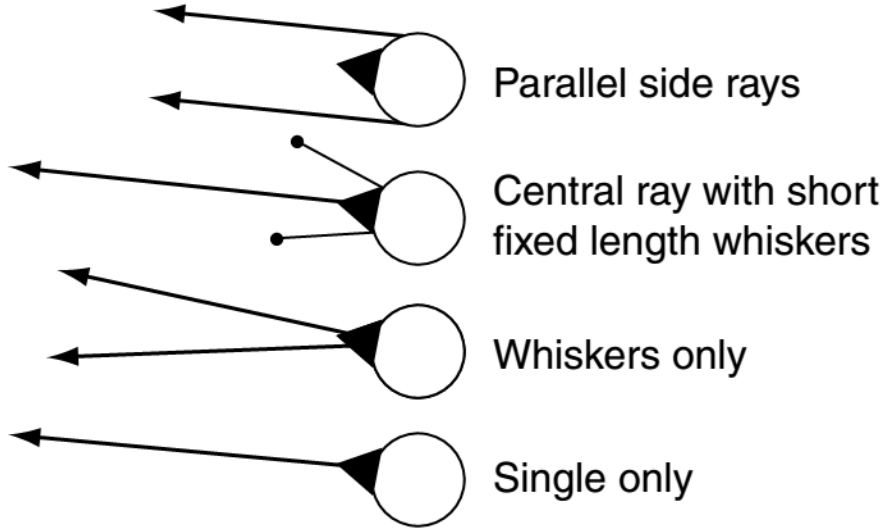
Millington Fig 3.24



Obstacle Test – Single Ray Falls Short

- No hard and fast rules as to which is better

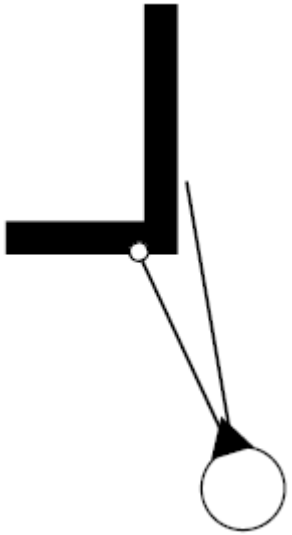


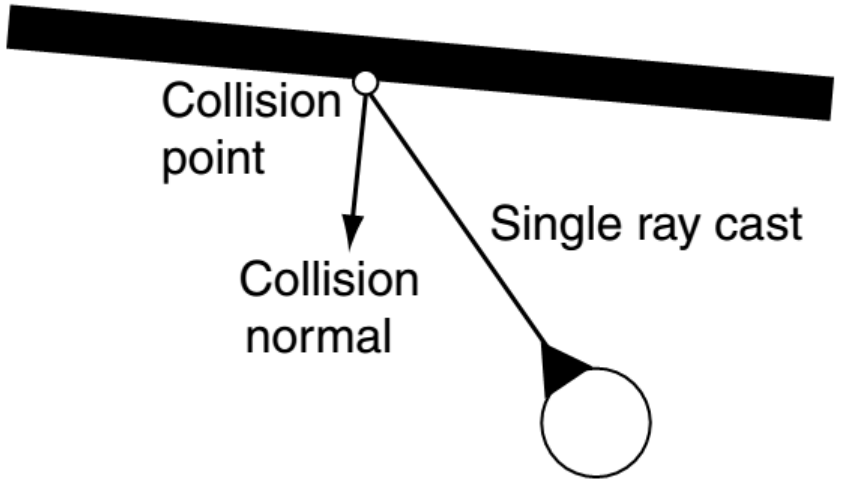


Often good start

The Corner Trap

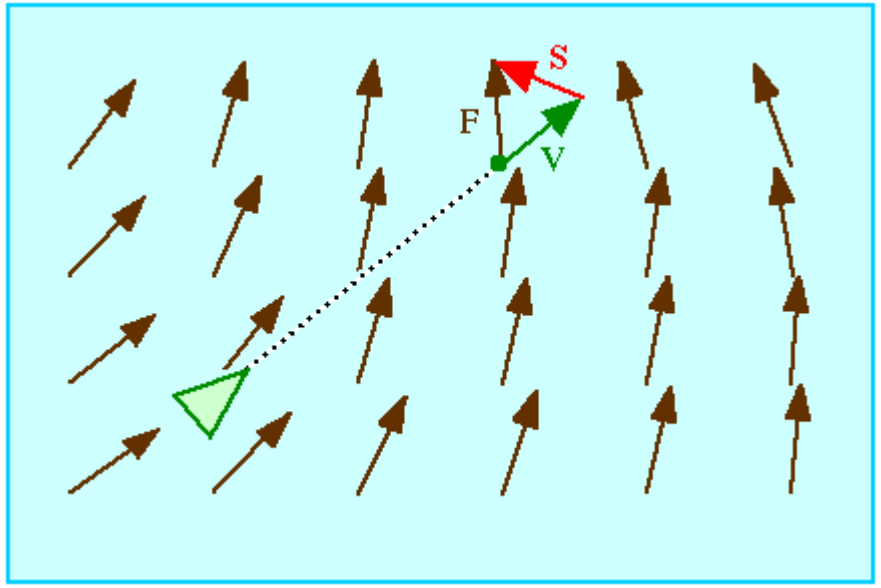
- multi-ray wall avoidance can get stuck on corners
- What happens below?





M&F 3.27

Flow/Force/Vector Fields

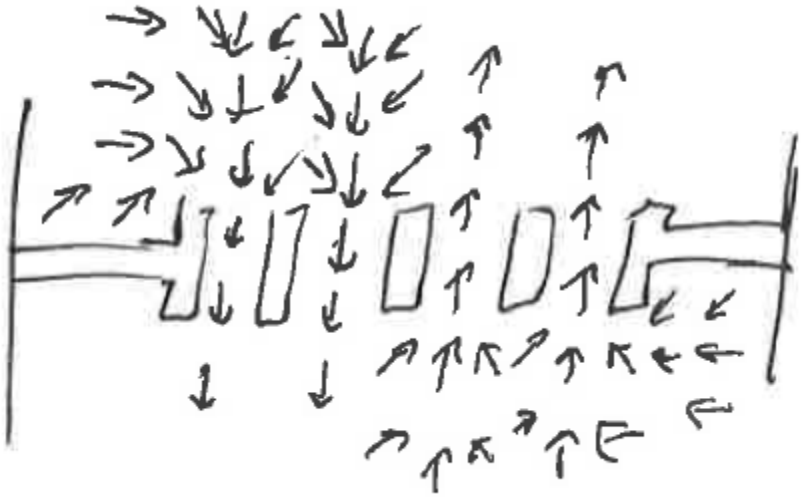


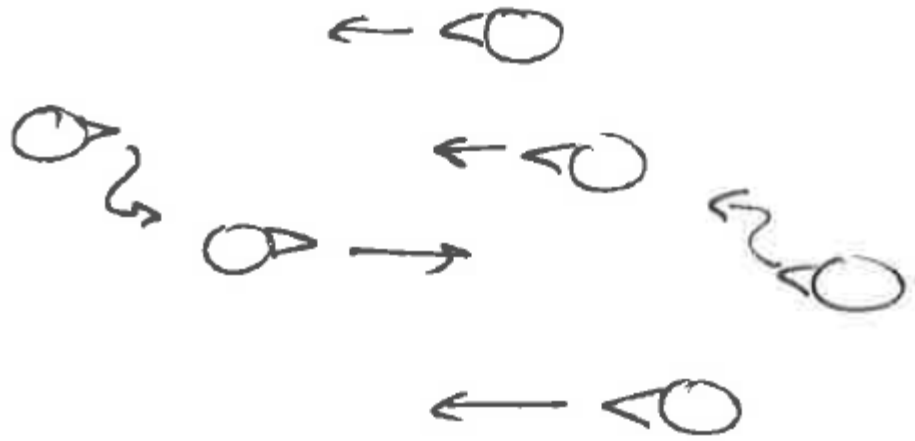
http://www.red3d.com/cwr/steer/gdc99/

- Motion specification without use of programming (can used by art staff directly)
- character steers to align its motion with the local tangent of *field*
  - Future position of a character is estimated, and flow field is sampled at that location.
  - This flow direction (vector F) is the “desired velocity”
  - The steering direction (vector S) is the difference between the current velocity (vector V) and the desired velocity (vector F)

Other approaches worth noting

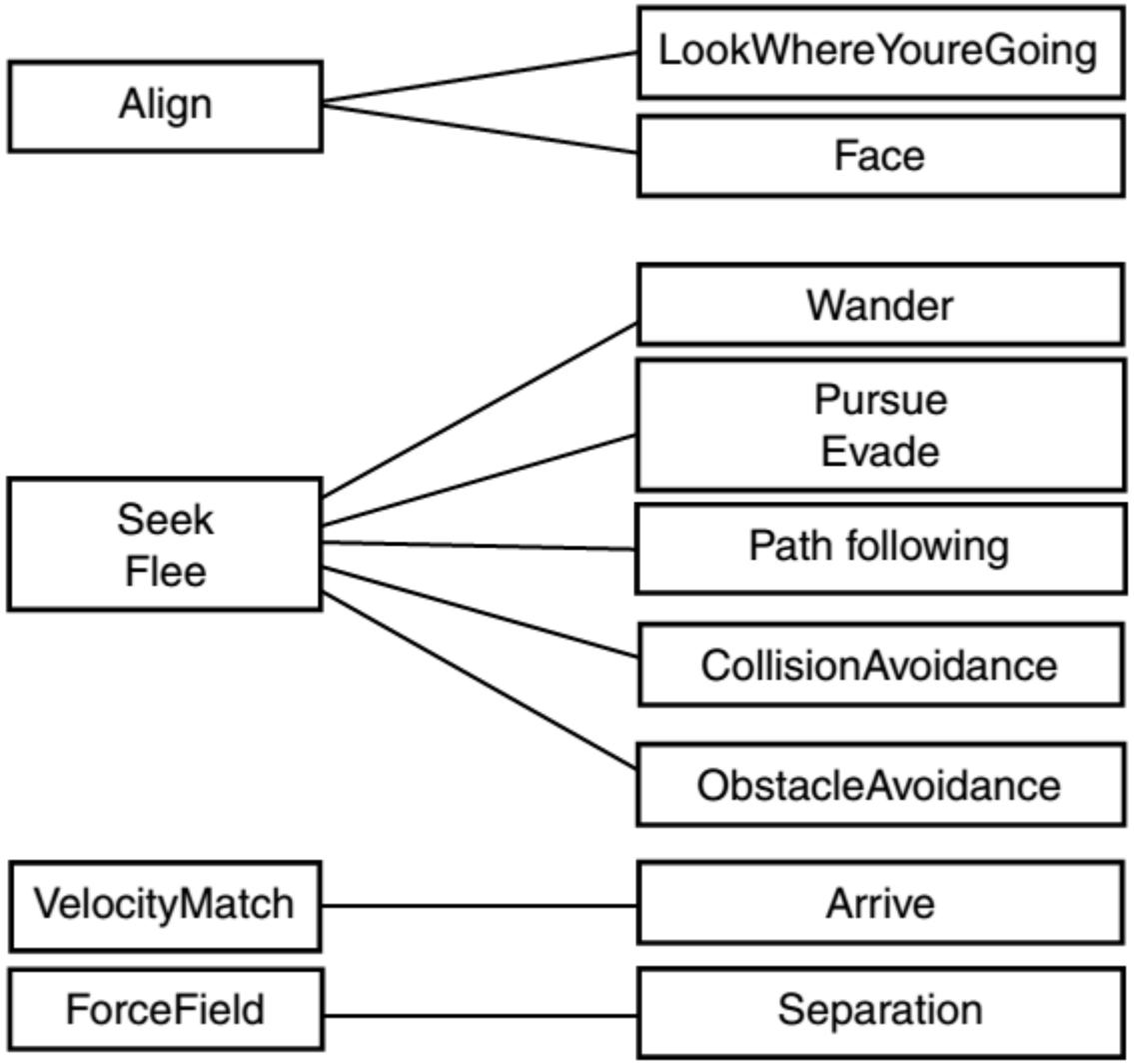
- Smart maps / smart environments
  - choke points are particularly problematic: kitchen door in restaurant
  - Navigation fields provide authorial control
- Lane formation





Composite Behaviors

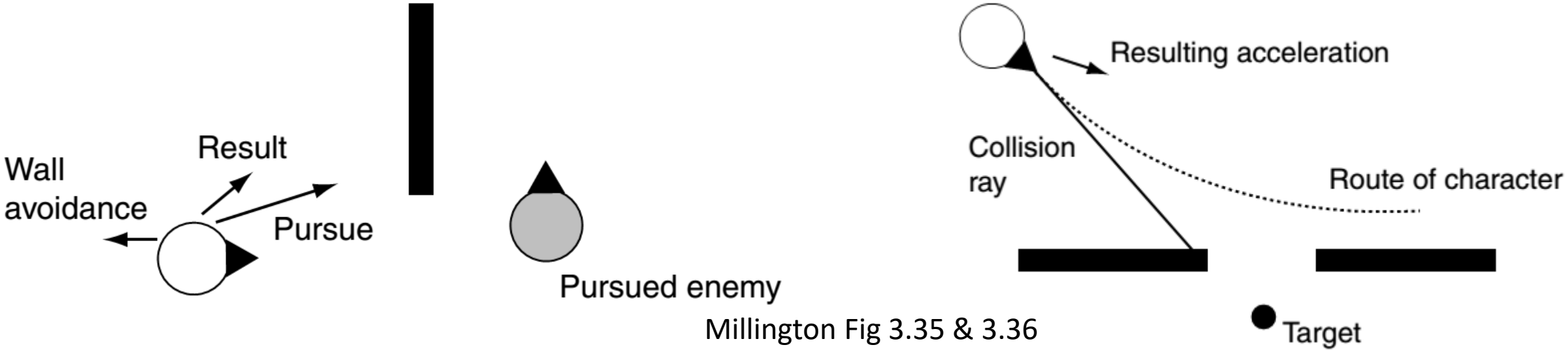
- Pursue / Evade
- Face / Look where going
- Wander
- Collision Avoidance
- Obstacle Avoidance
- Separation



Millington Fig 3.29

Variable Matching Conflicts

- Match position and orientation? Ok
- Match position and velocity? Conflict
- Moral: have individual variable matching algorithms, and conflict-resolving combination algorithm



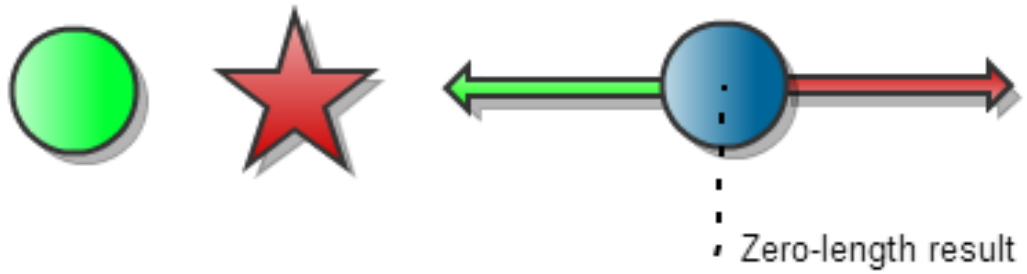
Millington Fig 3.35 & 3.36

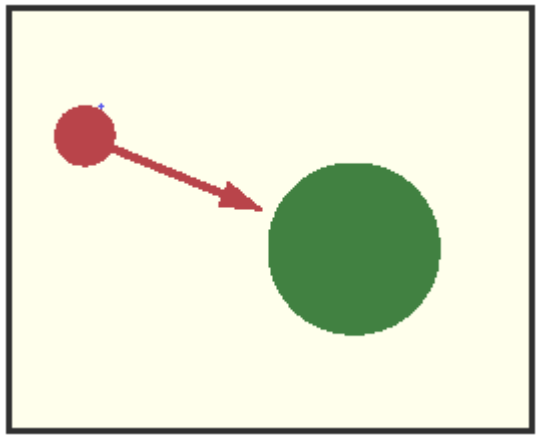
can't avoid an obstacle and chase

missing a narrow doorway

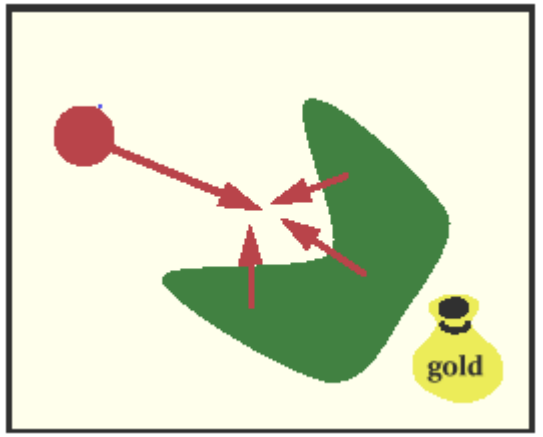
Combine Steering Behaviors: Problem

- What if steering behaviors are opposed?
- Zero vector!
- Or back and forth forever!
- Or orbiting!
- Need higher level control logic!

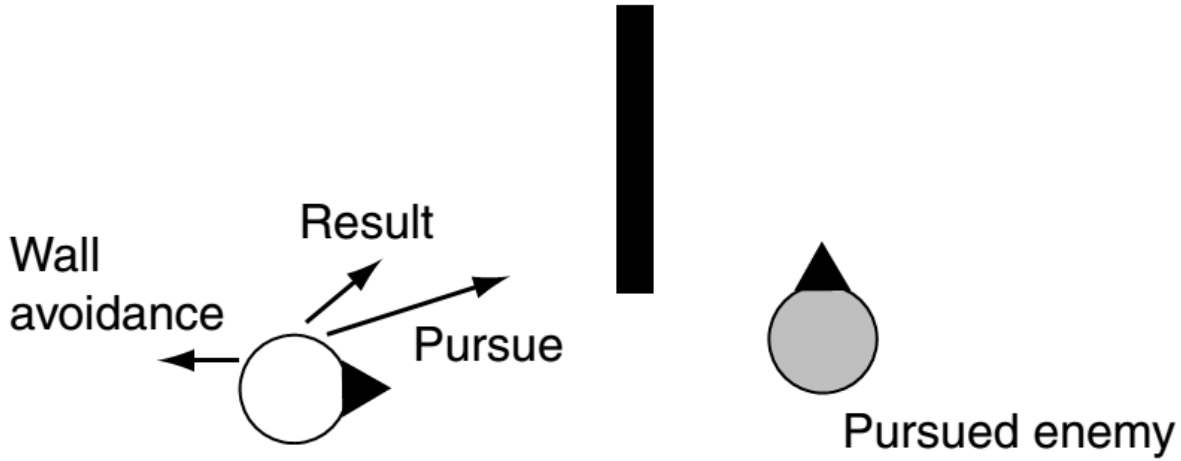




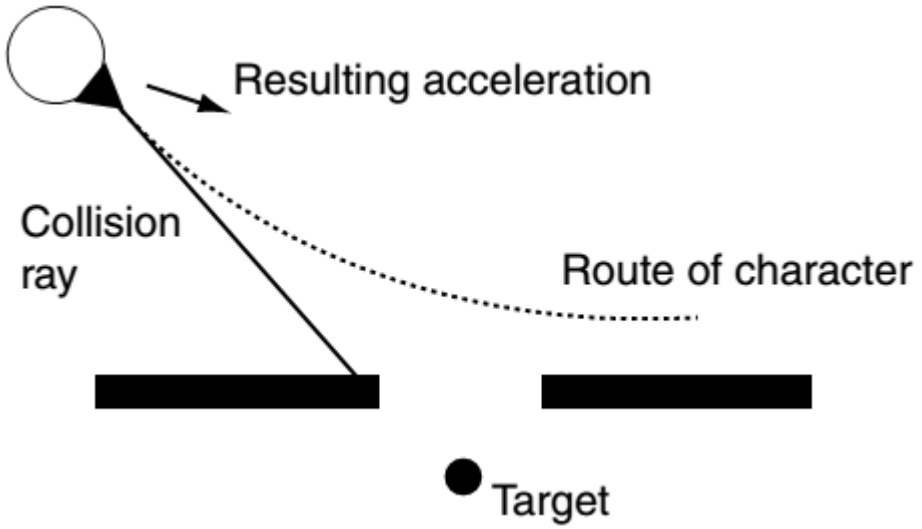
Exactly aligned



Forces balance out in dead end



can’t avoid an obstacle and chase

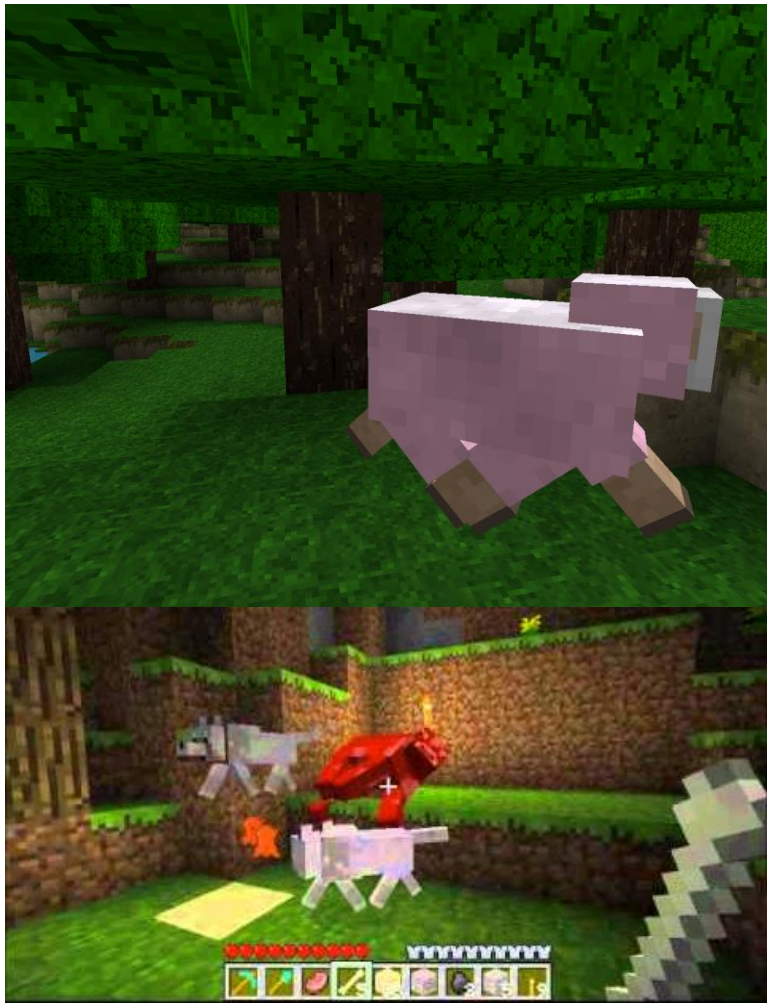


Missing a narrow doorway

Millington Fig 3.35 & 3.36

Combining Steering Behavior

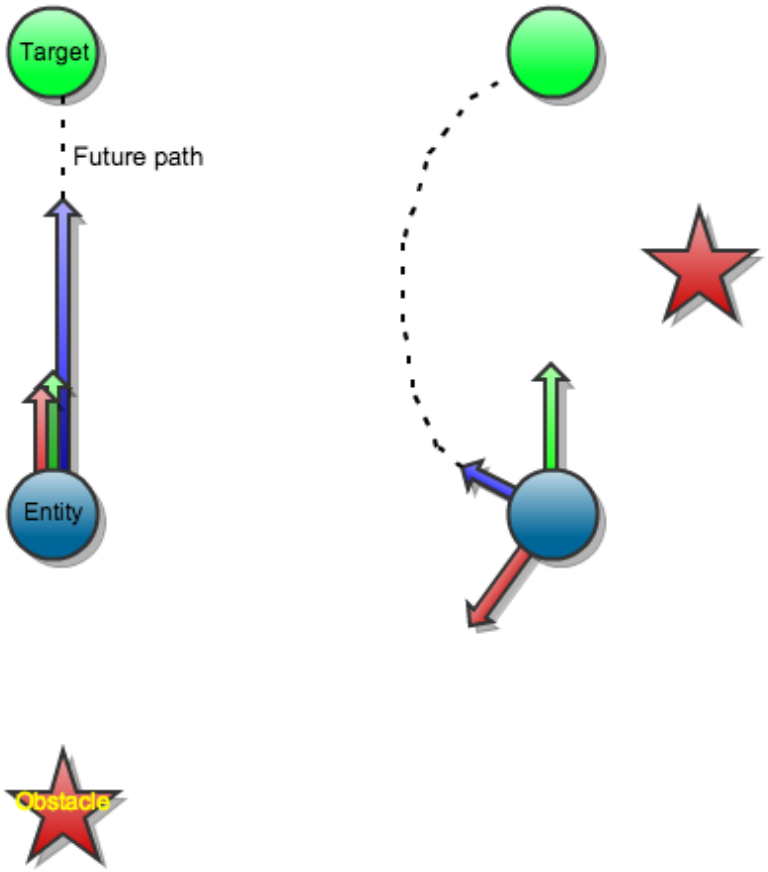
- Sum (w/ max speed enforced)
- (Weighted) Blending
  - Execute all steering behaviors
  - Combine results by calculating a compromise based on weights
    - Example: Flocking based on separation and cohesion
- Fixed priorities
- Arbitration
  - Selects one proposed steering
- Not mutually exclusive
- Emergent Behavior

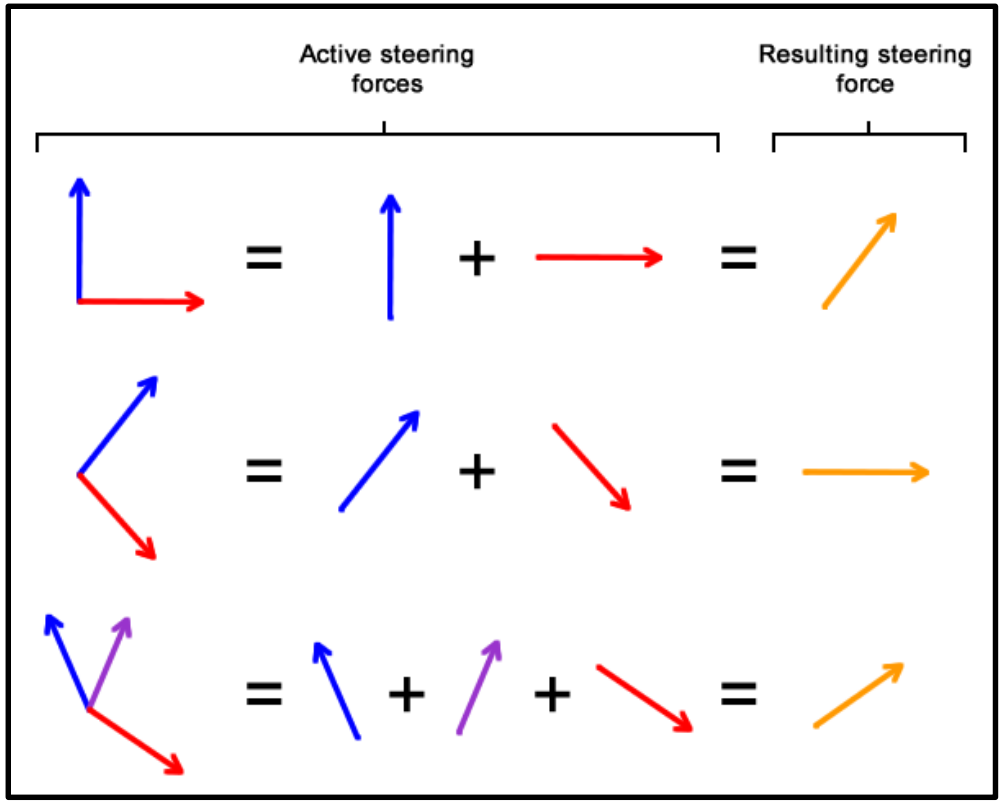


Weighted Blending

- Simplest way to combine steering behaviors
- Weighted linear sum of accelerations from all involved steering behaviors
- Post-processing velocity threshold
- E.g. rioting crowd may have 1*sep + 1*cohes
- Finding “right” weight can be challenging
  - Characters can get stuck (equilibrium)
  - Constrained environments (conflicts)
  - Jidder

Multiple Steering Goals? Combining steering behaviors





(static, kinematic, dynamic) Movement
Steering, **Flocking**, Formations

2019-09-16

M&F 3.1-3.4

B 3

http://www.red3d.com/cwr/steer/gdc99/

https://en.wikipedia.org/wiki/Swarm_behaviour

They’re flocking this way

https://www.youtube.com/watch?v=nM-RPO10aPY

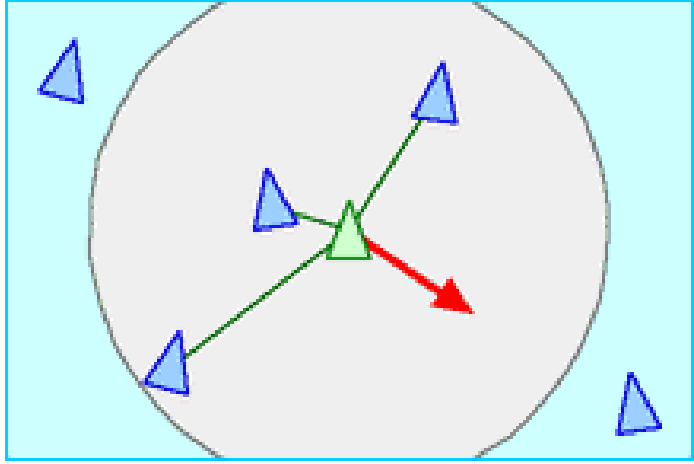
https://www.youtube.com/watch?v=QbUPfMXXQIY

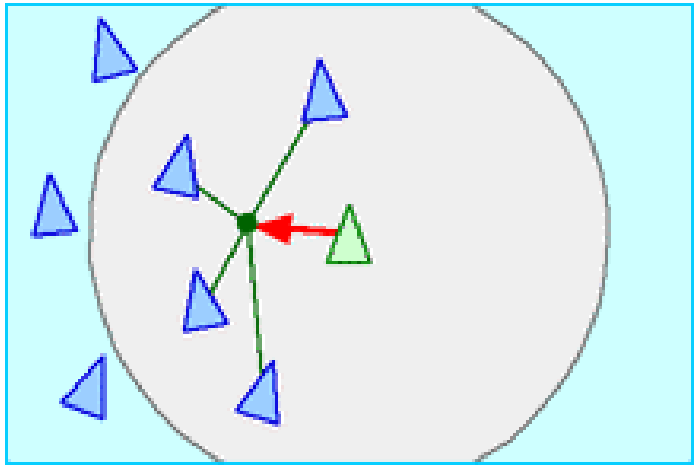
Problems

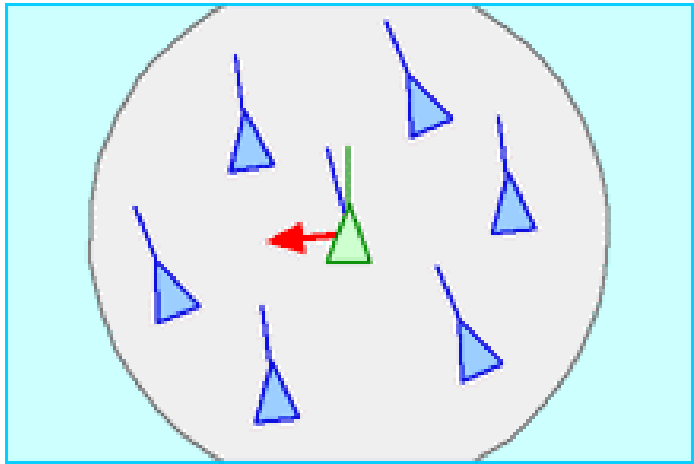
- Bunching:
  - https://www.youtube.com/watch?v=ZIAmoRsu3Z0&feature=youtu.be&list=PLxGbBc3OuMgg7OuyLfvXQLR6HKcoglCfG&t=1833
  - AIIDE 2015 keynote, Adam Noonchester. “AI In The Awesomepocalypse”
  - Sunset Overdrive: IGN 9.0 “Awesome”, Editors’ choice
- Too close:
  - https://youtu.be/ZIAmoRsu3Z0?list=PLxGbBc3OuMgg7OuyLfvXQLR6HKcoglCfG&t=1713

Flocking and Swarming

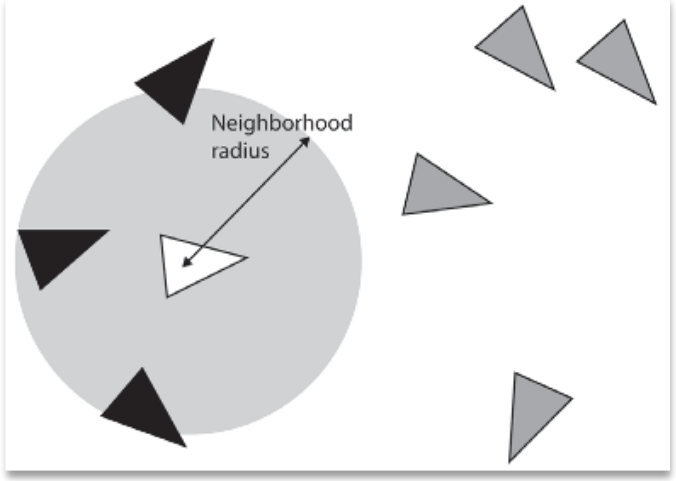
- Craig Reynold's "boids" (Flocking != Swarming)
  - https://www.youtube.com/watch?v=86iQiV3-3IA
  - https://www.youtube.com/watch?v=QbUPfMXXQIY
  - Simulated (apparent behavior of) birds, 1986
  - Blends three steering mechanisms (ordered)
    - Separation: Move away from other birds that are too close
    - Cohesion: Move to center of mass of flock
    - Alignment: Match orientation and velocity of flock
  - Equal Weights for simple flocking behavior



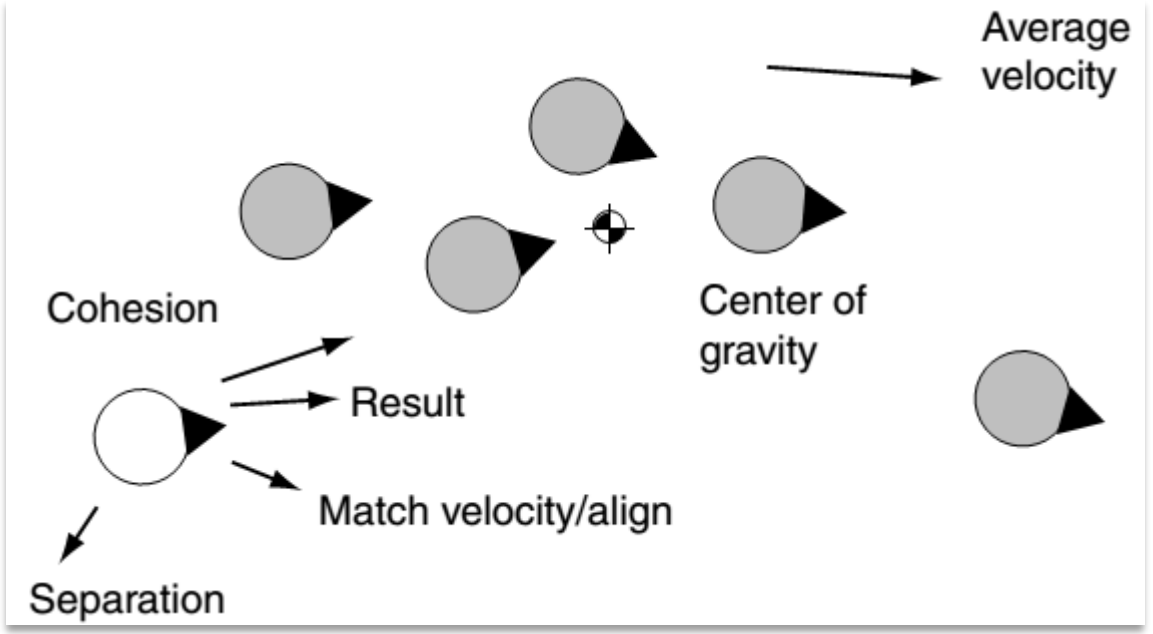




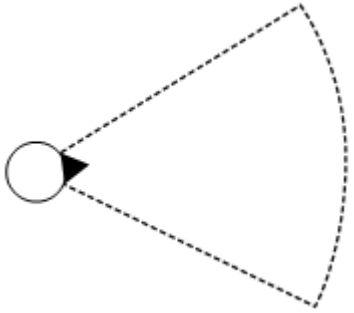
But 1st: won't you be my neighbor



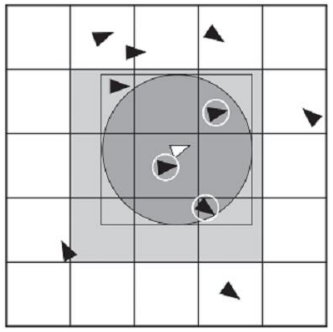
Buckland Fig 3.15



Millington Fig 3.31



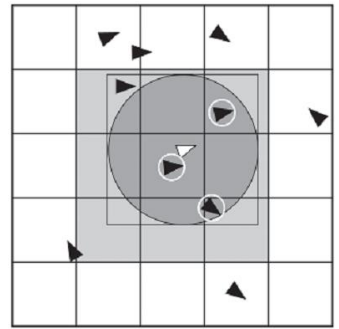
Millington Fig 3.32



Buckland Fig 3.18

Recall findNearestWaypoint()

- Most engines provide a rapid “nearest” function for objects
- Spatial partitioning w/ special data structures:
  - Quad-trees (2d), oct-trees (3d), *k*-d trees
  - Binary space partitioning (BSP tree): https://en.wikipedia.org/wiki/Binary_space_partitioning
  - Multi-resolution maps (hierarchical grids)
- The gain over all-pairs techniques depends on number of agents/objects
  - Brute force: $O(n^2)$ //every boid to each other



Buckland Fig 3.18

Boids – bin-lattice

- Spatial sub-division
- When boid moves, check to see if it is in a new bin (update accordingly)
- *O(n k)* – *k* is number of surrounding bins to consider

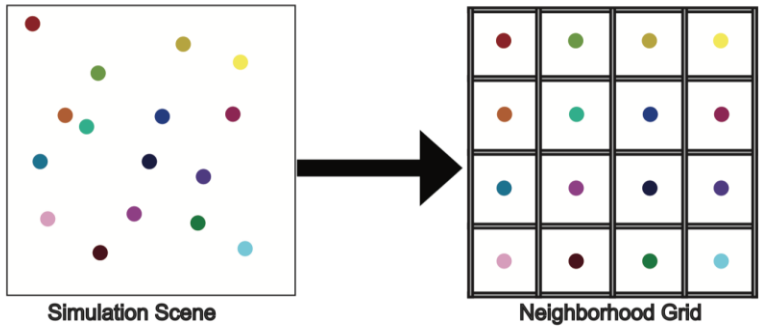


Figure 2: *Construction of the Neighborhood grid in a top-down camera.*

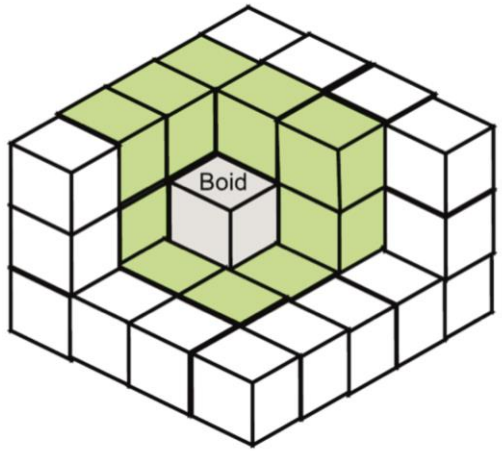


Figure 3: *Example of the neighborhood grid with radius = 1.*

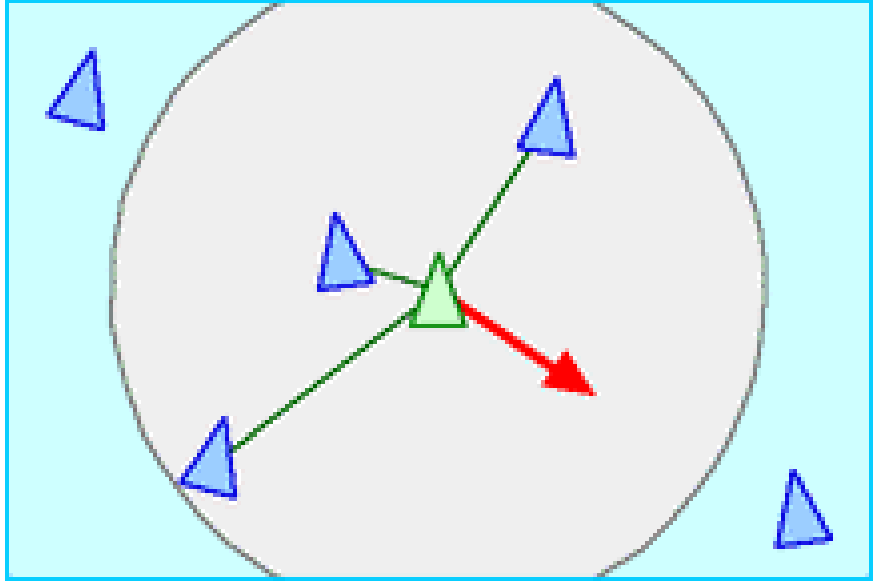
https://pdfs.semanticscholar.org/4183/faeef708a56b988742b5572fce9174caec7b.pdf

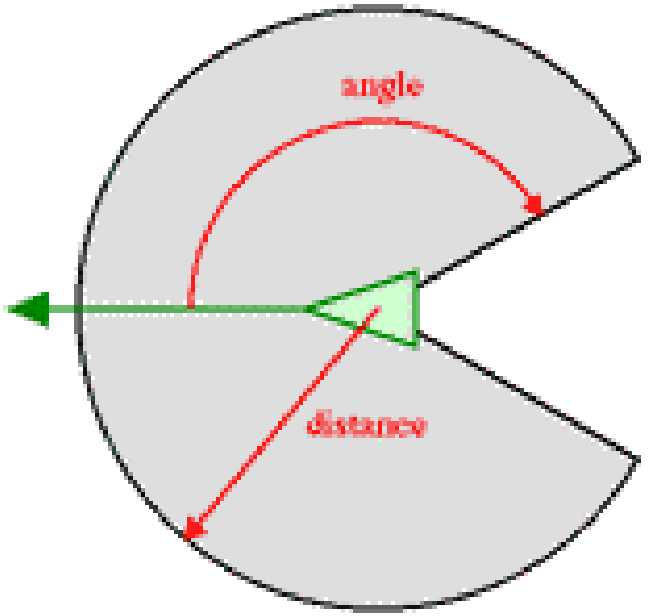
Demo

- Another big shoal (neighbors)

Separation

- Steer to avoid crowding local flockmates
  - Force to steer a bot away from neighbors
  - Neighborhood is a sphere of certain radius, or possibly a cone of perception
  - The vector to each bot under consideration is normalized, divided by the distance to the neighbor, and added to the steering force.

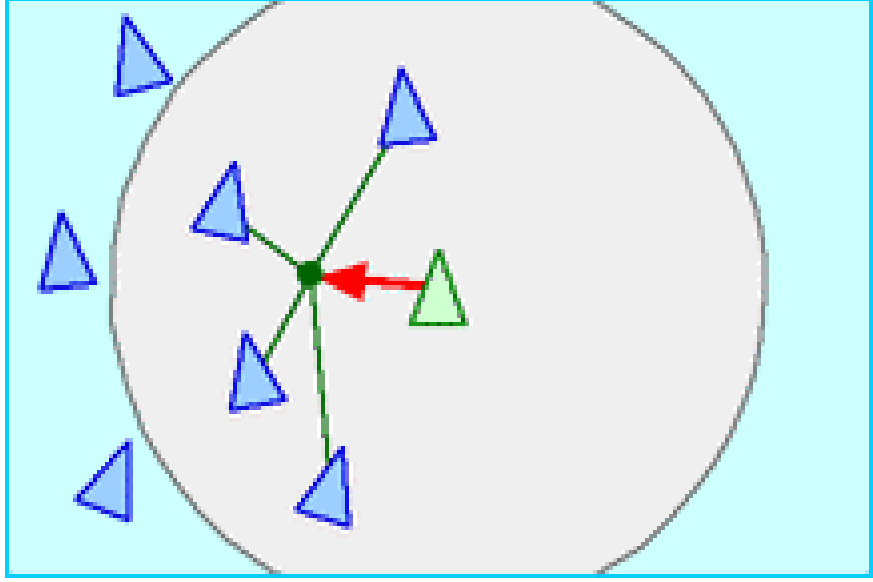




http://www.red3d.com/cwr/boids/

Cohesion

- Steer to average **position** (center of mass) of local flockmates
  - Desired position (center of mass): iterate through all neighbors and average their positions
  - Seek to desired position

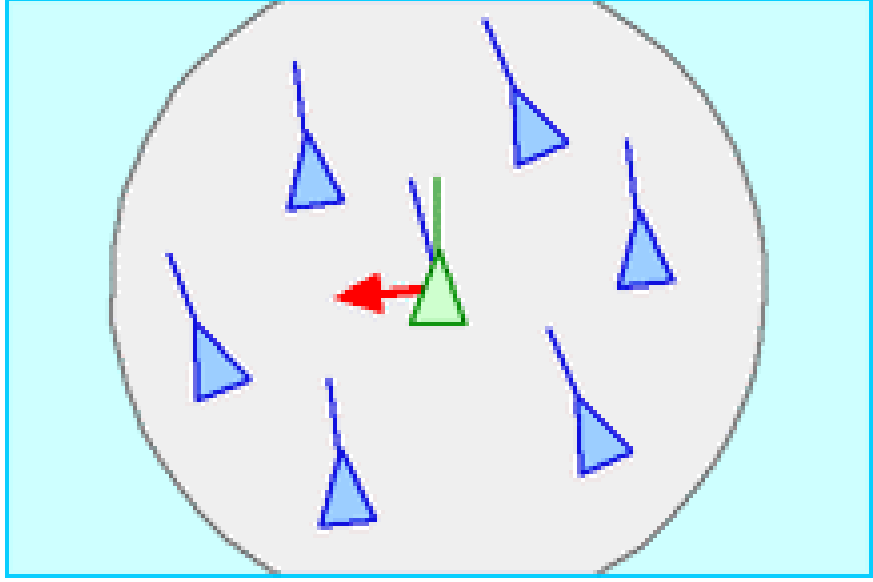


* Center of mass is the average position (X,Y,Z) of boids in neighborhood.

http://www.red3d.com/cwr/boids/

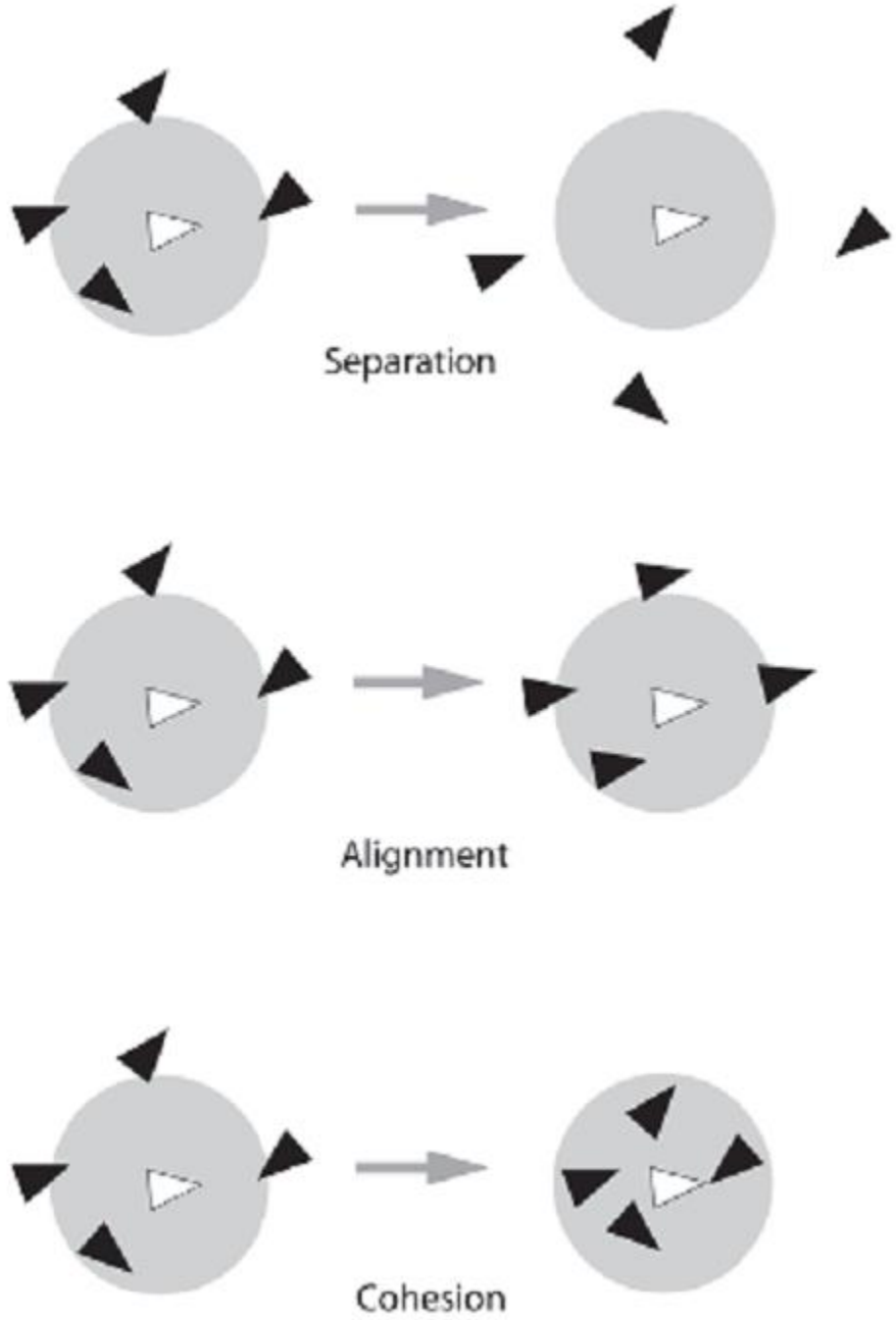
Alignment

- Steer towards average **heading**
  - Attempts to keep bots aligned with neighbors
  - Desired heading: iterate through all neighbors and average their heading vectors
  - For each neighbor, subtract bot's heading from desired heading



* Average heading and velocity of other boids in neighborhood

http://www.red3d.com/cwr/boids/



Buckland Fig 3.16

Demo

- Flocking (turn on and off)
- Big shoal (blending other behaviors)

Flocking Demos

- http://www.red3d.com/cwr/boids/
- http://www.red3d.com/cwr/boids/applet/

See Also

- M Ch 3, B Ch 3 (& Ch 1)
- Source from Millington
  - https://github.com/idmillington/aicore
- Java-based animations (combined behaviors)
  - http://www.red3d.com/cwr/steer/
- http://www.cse.scu.edu/~tschwarz/coen266_09/PPT/Movement%20for%20Gaming.ppt