**The three rules**

Stated briefly as rules, and in **order of decreasing precedence**, the behaviors that lead to simulated flocking are:

1. Collision Avoidance (**Separation**): avoid collisions with nearby flockmates
2. Velocity Matching (**Alignment**): attempt to match velocity with nearby flockmates
3. Flock Centering (**Cohesion**): attempt to stay close to nearby flockmates

Velocity is a vector quantity, referring to the combination of heading and speed. The meaning nearby in these rules is key to the flocking process. Generally one boid's awareness of another is based on the distance and direction of the offset vector between them.

Static collision avoidance and dynamic velocity matching are **complementary**. Together they ensure that the members of a simulated flock are free to fly within the crowded skies of the flock's interior without running into one another. Collision avoidance is the urge to steer away from an imminent impact. **Static collision avoidance** is based **on the relative position** of the flockmates and ignores their velocity. Conversely, **velocity matching** is based only **on velocity** and ignores position. It is a predictive version of collision avoidance: if the boid does a good job of matching velocity with its neighbors, it is unlikely that it will collide with any of them any time soon. Static collision avoidance serves to establish the minimum required separation distance; velocity matching tends to maintain it.

Flock centering makes a boid want to be near the center of the flock. Because each boid has a localized perception of the world. "**center of the flock" actually means the center of the nearby flockmates**. Flock centering causes the boid to fly in a direction that moves it closer to the centroid of the nearby boids. if a boid is deep inside a flock, the population density in its neighborhood is roughly homogeneous; the boid density is approximately the same in all directions. In this case, the centroid of the neighborhood boids is approximately at the center of the neighborhood, so the flock centering urge is small. But if a boid is on the boundary of the flock, its neighboring boids are on one side. The centroid of the neighborhood boids is displaced from the center of the neighborhood toward the body of the flock. Here the flock centering urge is stronger and the flight path will be deflected somewhat toward the local flock center.

Real flocks sometimes split apart to go around an obstacle. To be realistic, the simulated flock model must also have this ability. **Flock centering correctly allows simulated flocks to bifurcate**. As long as an individual boid can stay close to its nearby neighbors, it does not care if the rest of the flock turns away. More simplistic models proposed for flock organization (such as a central force model or a follow the designated leader model) do not allow splits.

The flock model presented here is a better model of a school or a herd than a flock. Fish in murky water (and land animals with their inability to see past their herdmates) have a limited, short-range perception of their environment. Birds, especially those on the outside of a flock, have excellent long-range "visual perception." Presumably this allows widely separated flocks to join together. If the flock centering urge was completely localized, when two flocks got a certain distance apart they would ignore each other. Long-range vision seems to play a part in the incredibly rapid propagation of a maneuver wave" through a flock of birds. It has been shown that the speed of propagation of this wavefront reaches three times the speed implied by the measured startle reaction time of the individual birds.

**Controlling the swarm direction**

The behaviors discussed so far provide for the ability of individual birds to fly and participate in happy aimless flocking. But to combine flock simulations with other animated action, we need more direct control over the flock. We would like to **direct specific action at specific times** (for example, "the flock enters from the left at :02.3 seconds into the sequence, turns to fly directly upward at :03.5, and is out of the frame at :04.0").

The current implementation of the boid model has several facilities to direct the motion and timing of the flock action. First, the simulations are run under the control of a general-purpose animation scripting system. The details of that scripting system are not relevant here except that, in addition to the typical interactive motion control facilities, it provides the ability to schedule the invocation of user-supplied software (such as the flock model) on a frame-by-frame basis. This scripting facility is the basic tool used to describe the timing of various flock actions. It also allows flexible control over the time-varying values of parameters, which can be passed down to the simulation software. Finally, the script is used to set up and animate all nonbehavioral aspects of the scene, such as backgrounds, lighting, camera motion, and other visible objects.

The primary tool for scripting the flock's path is the migratory urge built into the boid model. In the current model this urge is specified in terms of a global target, either as a global direction (as in "going Z for the winter") or as a global position-a target point toward which all birds fly. The model computes a **bounded acceleration** that **incrementally turns** the boid toward its migratory target.

With the scripting system. we can animate a dynamic parameter whose value is. a global position vector or a global direction vector. This parameter can be passed to the flock, which can in turn pass it along to all boids, each of which sets its own "**migratory goal register**." Hence the global migratory behavior of all birds can be directly controlled from the script. (Of course, it is not necessary to alter all boids at the same time, for example, the delay could be a function of their present position in space. Real flocks do not change direction simultaneously, but rather the turn starts with a single bird and spreads quickly across the flock like a shock wave.)

We can lead the flock around by animating the goal point along the desired path, somewhat ahead of the flock. Even if the migratory goal point is changed abruptly the path of each boid still is relatively smooth because of the flight model's simulated conservation of momentum. This means that the boid's own flight dynamics implement a form of smoothing interpolation between "control points."

*To balance the workload, discuss about potential options of enforcing splitting and rejoining of the swarm using different migratory goals for parts of swarm. How would you implement the incremental nature of the migratory urge that would yield natural results?*

**Avoiding obstacles with the swarm**

The most interesting motion of a simulated flock comes from interaction with other objects in the environment. The isolated behavior of a flock tends to reach a steady state and becomes rather sterile. The flock can be seen as a relaxation solution to the constraints implied by its behaviors. For example, the conflicting urges of flock centering and collision avoidance do not lead to constant back and forth motion, but rather the boids eventually strike a **balance between the two urges** (the degree of damping controls how soon this balance is reached). **Environmental obstacles** and the boid's attempts to navigate around them **increase the apparent complexity** of the behavior of the flock. (In fact the complexity of real flocks might be due largely to the complexity of the natural environment.)

Environmental obstacles are also important from the standpoint of modeling the scene in which we wish to place the flock. If the flock is scripted to fly under a bridge and around a tree, we must be able to represent the geometric shape and dimension of these obstacles. The approach taken here is to independently model the "shape for rendering" and the "shape for collision avoidance." The types of shapes currently used for environmental obstacles are much less complicated than the models used for rendering of computer graphic models. The current work implements two types of shapes of environmental collision avoidance. One is based on the **force field concept**, which works in undemanding situations but has some shortcomings. The other model called **steer-to-avoid** is more robust and seems closer in spirit to the natural mechanism.

The force field model postulates a field of repulsion force emanating from the obstacle out into space; the boids are increasingly repulsed as they get closer to the obstacle. This scheme is easy to model; the geometry of the field is usually fairly simple and so an avoidance acceleration can be directly calculated from the field equation. These models can produce good results but they also have drawbacks that are apparent on close examination. If a boid approaches an obstacle surrounded by a force field at an angle such that it is exactly opposite to the direction of the force field, the boid will not turn away. In this case the force field serves only to slow the boid by accelerating it backwards and provides no side thrust at all. The worst reaction to an impending collision is to fail to turn. Force fields also cause problems with "peripheral vision." The boid should notice and turn away from a wall as it flies toward it, but the wall should be ignored if the boid is flying alongside it. Finally, force fields tend to **be too strong close up** and **too weak far away**; avoiding an obstacle should involve long-range planning rather than **panicky corrections at the last minute**.

**Steer-to-avoid** is a better simulation of a natural bird guided by vision. The boid considers **only obstacle**s directly **in front** of it. (It finds the intersection, if any, of its local Z axis with the obstacle.) Working in local perspective space, it finds the silhouette edge of the obstacle closest to the point of eventual impact. A radial vector is computed which will aim the boid at a point one body length beyond that silhouette edge. Currently steer-to avoid has been implemented for several obstacle shapes: spheres, cylinders, planes, and boxes. Collision avoidance for arbitrary convex polyhedral obstacles is being developed.

**Obstacles are not necessarily fixed in space**; they can be animated around by the script during the animation. Or more interestingly, the obstacles can be behavioral characters. Sparrows might flock around a group of obstacles that is in fact a herd of elephants. Similarly, behavioral obstacles might not merely be in the way; they might be objects of fear such as predators. **It has been noted that natural flocking instincts seem to be sharpened by predators**.

### Arbitrating Independent Behaviors

The **three behavioral urges** associated with flocking (separation, cohesion, alignment) each produce an isolated suggestion about which way to steer the boid. These are **expressed as acceleration** requests. Each behavior says: "If I were in charge, I would accelerate in that direction." The acceleration request is in terms of a 3D vector that, by system convention, is truncated to unit magnitude or less. Each behavior has several parameters that control its function; one is a "**strength**," a fractional value between zero and one that can further attenuate the acceleration request. It is up to the navigation module of the boid brain to collect all relevant acceleration requests and then determine a single behaviorally desired acceleration. It must combine, prioritize, and arbitrate between potentially conflicting urges. The pilot module takes the acceleration desired by the navigation module and passes it to the flight module, which attempts to fly in that direction.

The easiest way to combine acceleration requests is to **average** them. Because of the included "strength" factors, this is actually a weighted average. The relative strength of one behavior to another can be defined this way, but it is a precarious interrelationship that is difficult to adjust. An early version of the boid model showed that navigation by simple weighted averaging of acceleration requests works "pretty well." A boid that chooses its course this way will fly a reasonable course under typical conditions. But in critical situations, such as potential collision with obstacles, conflicts must be resolved in a timely manner. During high-speed flight, hesitation or indecision is the wrong response to a brick wall dead ahead.

The main cause of indecision is that each behavior might be shouting advice about which way to turn to avoid disaster, but if those acceleration requests happen to lie in approximately opposite directions, they will largely cancel out under a simple weighted averaging scheme. The boid would make a very small turn and so continue in the same direction, perhaps to crash into the obstacle. Even when the urges do not cancel out, averaging leads to other problems. Consider flying over a gridwork of city streets between the skyscrapers; while "fly north" or "fly east" might be good ideas, it would be a bad idea to combine them as "fly northeast."

Techniques from artificial intelligence, such as expert systems, can be used to arbitrate conflicting opinions. However, a less complex approach is taken in the current implementation. **Prioritized acceleration allocation** is based on a strict priority ordering of all component behaviors, hence of the consideration of their acceleration requests. (This ordering can change to suit dynamic conditions.) The acceleration requests are considered in priority order and added into an accumulator. The magnitude of each request is measured and added into another accumulator. This process continues until the sum of the accumulated magnitudes gets larger than the maximum acceleration value, which is a parameter of each boid. The last acceleration request is trimmed back to compensate for the excess of accumulated magnitude. The point is that a fixed amount of acceleration is under the control of the navigation module; this acceleration is parceled out to satisfy the acceleration request of the various behaviors in order of priority. In an emergency the acceleration would be allocated to satisfy the most pressing needs first; if all available acceleration is "used up," the less pressing behaviors might be temporarily unsatisfied. For example. the flock centering urge could be correctly ignored temporarily in favor of a maneuver to avoid a static obstacle.

**Simulated Perception**

The boid model does not directly simulate the senses used by real animals during flocking (vision and hearing) or schooling (vision and fishes' unique "lateral line" structure that provides a certain amount of pressure imaging ability). Rather the **perception model** tries to make available to the behavior model **approximately** the same information that is available to a real animal as **the end result of its perceptual and cognitive processes**.

This is primarily a matter of filtering out the surplus information that is available to the software that implements the boid's behavior. Simulated boids have direct access to the geometric database that describes the exact position, orientation, and velocity of all objects in the environment. The real bird's information about the world is severely limited because it perceives through imperfect senses and because its nearby flockmates hide those farther away. This is even more pronounced in herding animals because they are all constrained to be in the same plane. In fish schools. visual perception of neighboring fish is further limited by the scattering and absorption of light by the sometimes murky water between them These factors combine to strongly localize the information available to each animal.

Not only is it unrealistic to give each simulated boid perfect and complete information about the world, it is just plain wrong and leads to obvious failures of the behavior model. Before the current implementation of localized flock centering behavior was implemented. the flocks used a **central force model**. This leads to **unusual effects** such as causing all members of a widely scattered flock to simultaneously converge toward the flock's centroid. An interesting result of the experiments reported in this paper is that the aggregate motion that we intuitively recognize as **"flocking"** (or schooling or herding) **depends** **upon** a limited, **localized view** of the world.

The behaviors that make up the flocking model are stated in terms of "nearby flockmates." In the current implementation, the neighborhood is defined as a **spherical zone of sensitivity** centered at the boid's local origin. The magnitude of the sensitivity is defined as an inverse exponential of distance. Hence the neighborhood is defined by two parameters: a radius and exponent. There is reason to believe that this **field of sensitivity** should realistically be **exaggerated in the forward direction** and probably by an amount **proportional to the boid's speed**. Being in motion requires an increased awareness of what lies ahead, and this requirement increases with speed. A forward-weighted sensitivity zone would probably also improve the behavior in the current implementation of boids at the leading edge of a flock, who tend to get distracted by the flock behind them. Because of the way their heads and eyes are arranged, real birds have a wide field of view (about 300 degrees), but the zone of overlap from both eyes is small (10 to 15 degrees). Hence the bird has stereo depth perception only in a very small, forward-oriented cone. Research is currently under way on models of forward-weighted perception for boids.

In an early version of the flock model, the metrics of attraction and repulsion were weighted linearly by distance. This spring-like model produced a bouncy flock action, fine perhaps for a cartoony characterization, but not very realistic. **The model was changed to use an inverse square of the distance**. This more gravity-like model produced what appeared to be a more natural, better damped flock model. This correlated well with the carefully controlled quantitative studies that Brian Partridge made of the spatial relationships of schooling fish; he found that "a fish is much more strongly influenced by its near neighbors than it is by the distant members of the school. The boid perception model is quite ad hoc and avoids actually simulating vision. Artificial vision is an extremely complex problem and is far beyond the scope of this work. But if boids could "see" their environment, they would be better at path planning than the current model. It is possible to construct simple maze like shapes that would confuse the current boid model but would be easily solved by a boid with vision.