generalized virtual ant with a rule string that consists of all Os or all 1s will never do anything more interesting than travel around in a little square. A not so obvious result is due to E. G. D. Cohen and X. P. Kong (see the digression box for a similar result); it states that any virtual ant defined by a rule string that has at least one 0 and one 1 cannot be contained in a finite-sized box, that is, it will always escape any boundary that you try to place around it.

Highway-building, as a property of virtual ants, is found in many other types of ants besides Langton's. Some examples of generalized virtual ants will behave chaoticly for hundreds of thousands of steps and only then spontaneously break into highway-building behavior. For other examples, no one knows if they will ever build highways because chaotic patterns persist even after hundreds of millions of time steps.

Ian Stewart (1994) has made an interesting observation regarding our lack of knowledge about the long-term behavior of some of these virtual ants. To paraphrase, for any of these ants we know their Theory of Everything, in that all of the "physical" laws that govern the ant's universe are simple and known to us. We also know the initial configuration of the ant's universe. Yet we are helpless to answer a simple question: Does the ant ever build a highway? Putting this all in perspective, if physicists ever uncover a Theory of Everything for our universe, and even if we deduce the initial state of the universe, we may still be helpless to deduce the long-term behavior of our own universe. Thus, as Stewart has said, the Theory of Everything in this case predicts everything but explains nothing.

It may be that a highway-building proof exists for these ants. We don't know at this point. But as we saw in the last chapter, other cellular automata that are only moderately more complicated than these virtual ants are known to be capable of universal computation, and it is therefore known to be impossible to prove many things about their long-term behaviors.

16.3
Flocks, Herds, and Schools

In the previous sections we saw how simple agents acting in isolation could display self-organizational properties despite their simplistic behavioral limitations. In the case of termites, adding more agents to the simulation did no harm, in that self-organization persisted even when multiple termites were acting as if they were alone; however, two termites were incapable of producing a qualitatively different type of behavior than a single termite. For the virtual ants, we briefly saw how two or more ants could create structures that no single ant could create. In this section we will take these ideas to an extreme by witnessing a type of agent that always produces uninteresting behavior by itself, but displays a stunning variety of behaviors when interacting with many similar agents. Specifically, in this section, we will examine a model of how collections of animals, such as flocks, herds, and schools, move about

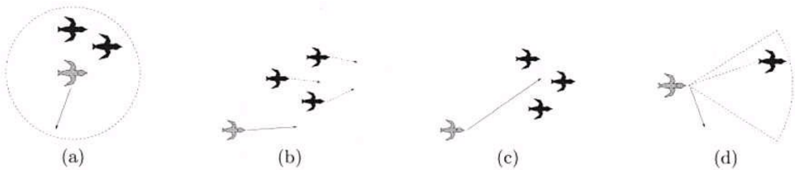

Figure 16.6
Four boid rules: (a) avoid flying too close to others; (b) copy near neighbors; (c) move towards center of perceived neighbors; (d) attempt to maintain clear view.

in a space in a way that appears to be orchestrated.

In the late 1980s, Craig Reynolds created a model of animal motion, named *boids*, that he used to simulate the motion of a flock of birds. Reynolds's approach was to make each boid in the flock an independent agent that attempts to follow a simple set of rules so as to independently optimize various goals. This approach is radically different from a more explicit technique that scripts the motion of each individual boid, since none of the boids—and not even the programmer—have any idea where the boids will eventually fly off to.

The goals that the boids try to achieve are very simple and are for the most part intuitive. The following list of rules explains these goals and the simplest technique that a hold can exploit to achieve each goal:

- **Avoidance**. Move away from boids that are too close, so as to reduce the chance of in-air collisions.
- **Copy**. Fly in the general direction that the flock is moving by averaging the other boids' velocities and directions.
- **Center**. Minimize exposure to the flock's exterior by moving toward the perceived center of the flock.
- **View**. Move laterally away from any boid that blocks the view.

Reynolds used only the first three goals; the fourth is my own creation that I added for no better reason than that it seemed like a good idea. We will see how the boids behave with and without the fourth rule later on. All of the rules are geometrically illustrated in Figure 16.6, which should be helpful in the discussion that follows.

The avoidance rule is probably the most fundamental, since it is the one rule that every boid can never completely ignore. In this spirit we consider the avoidance rule absolute, in that the copy and center rules are inactivated for any offending boid that invades another boid's personal space. This is an important heuristic because it makes little sense for a boid to simultaneously attempt to avoid, and to copy or center on, any other bolds that are too close.

The copy rule enforces a form of cohesion that keeps the flock together over the long term. Presumably, boids in a flock would want to stay together for many reasons (safety in numbers, stay with mate, etc.), but, as Reynolds has pointed out, the copy rule also acts as a first approximation to collision avoidance, since if every boid is flying at the same velocity and heading, the risk of collisions is reduced. Clearly, it is not very realistic for every boid to be aware of every other boid's velocity and heading. So, to make things more realistic, we allow the boids to have only a fixed viewing angle from which they can "see" other boids. Additionally, their "vision" is further limited by enforcing the constraint that they can see only a finite distance.

The center rule is a very greedy method for bolds to watch out for themselves at the expense of their neighbors. Since almost every type of locomotion group found in nature has a natural enemy in the form of a predator, it is to any individual agent's advantage to stay away from the edge of a flock, herd, pack, or school. After all, it is far better from an evolutionary point of view for an agent's neighbor to become a predator's meal than for itself to be the meal.[1] We place the same visual constraints on the center rule as we did for the copy rule, except for the fact that we allow the boids to use a different viewing radius for the purpose of averaging neighbors' positions. Thus, conceptually a boid can try to maintain the same heading and velocity as every other boid that it sees within a hundred yards or so, but it attempts to stay in the center only of a smaller group within 100 feet, for example. Notice that while the copy rule depends on the other boids' headings and speeds, the center rule depends only on the other bolds' positions.

As mentioned earlier, the view rule is my own addition. While the rule seems biologically plausible to me, the only fieldwork I have done on the subject is to watch geese from my backyard, so you should take it with the grain of salt it deserves. I added this last rule because the only way I could ever coerce Reynolds's boids into a "V" formation was to partially blind them with an unrealistic viewing angle. The view rule works by moving the boid in a direction perpendicular to the vector that joins the first bold and the boid that is interfering with its sight. Since there are two such perpendicular paths, the boid always chooses the direction that is closer to its original heading. This has the side affect that the view rule will never encourage a bold to slow down, which is probably not very realistic, but it still seems to have the desired effect. We also allow the boids to vary what they consider to be visual interference by having a parameter that defines a narrow region by an angle and distance.

[1]If this sounds a bit Machiavellian, consider the case of penguins jumping into water. If some penguins are safely in the water, then another penguin can safely assume that there aren't any predators around. But which penguin jumps in first if no penguins are already in the water? The characteristic of sacrificing one's self should be quickly removed from the gene pool, so how do penguins resolve the problem? Simple. They often try to push each other in first (Dawkins, 1976).

Since we have defined the different types of goals that a boid will attempt to achieve, we now need to consider how a boid will combine all of these urges into a single action. Since each rule specifies a suggested direction in which to fly, we take a weighted average of the four directions to yield a single new direction. It is also not realistic to give the boids the ability to instantaneously change direction, so we include a sort of momentum factor that makes the boid partially continue along its previous path. Mathematically, this looks like

$$\mathbf{v}_{new} = \mu \mathbf{v}_{old} + (1 - \mu)(\ _{avoid}\mathbf{v}_{avoid} + \ _{copy}\mathbf{v}_{copy} + \ _{center}\mathbf{v}_{center} + \ _{view}\mathbf{v}_{view}),$$

where all of the **v** terms are velocity vectors, all of the terms are weighting factors, and μ is the momentum term. With the new composite velocity vector, we can add it to the old position to get the new position:

$$\mathbf{p}_{new} = \mathbf{p}_{old} + \ \mathbf{v}_{new},$$

where the **p** terms are positional vectors and specifies a step size or time increment.

The weights for the rules can be varied to your liking, but I preferred something along the lines of

$$_{avoid} > \ _{view} > \ _{center} > \ _{copy},$$

which seems like a reasonable relationship between the four weights if we consider collision avoidance to be the most important rule for survival, and copying the least important. Moreover, the ordering seems to make sense temporally, in that when a bold needs to avoid an obstacle, it must act instantly, while staying with the rest of the flock is more of a long-term goal. But this is just my spin on things.

Putting all of this together, we can now look at some examples of boids in motion. Figures 16.7 and 16.8 show two examples of boids in flight with the view rule disabled. In the first example we can see how a disorganized collection of bolds will coalesce into a single flock. The figure really doesn't do the process justice because what you can't see in the figure are things like the boids jostling each other to get into the center of the flock, or how an isolated boid will all of a sudden spot a flock in the distance and zip across the screen to join the others.

Watching the boids in flight is a fascinating exercise. I would be embarrassed to tell you just how long I played with the simulation in the process of writing this chapter. You should try the simulation yourself.

Figure 16.8 shows another example of what happens when you change the "physics" of the boids' universe in a strange manner. As you can see, the boids quickly form into two swarm-like structures with the bolds orbiting each other in a cyclic manner. After a while, the smaller swarm on the left starts moving in an ever more eccentric manner because the boids in it periodically catch a glimpse of the larger swarm. Eventually, the smaller swarm becomes unstable and the boids leave it for the larger swarm. To coerce the boids into this type of behavior, I gave

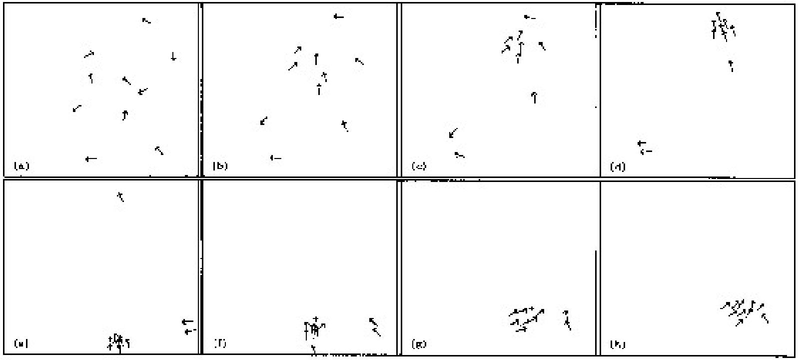

Figure 16.7
A collection of boids self-organize to form a flock

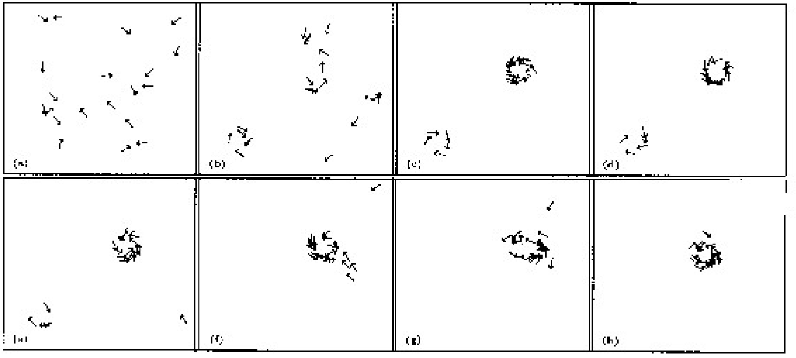

Figure 16.8
Changing the physics of the boids' universe allows for boid cycles.