tree." This is depicted in animation III-5 by drawing a line from every parent to each of its children.[14] The initial population is colored black. When a member of this population has a child, the new parent is colored red, the child green. Agents who are both parents and children are colored yellow. (Note that members of the initial population can never be yellow.)

It is interesting to watch the evolution of such genealogical networks. At the outset there are no connections since, in the initial population, no agents are related. However, after several generations, when none of the initial agents remains, all the agents on the sugarscape have some definite genealogical lineage. Notice that average fertility and the standard deviation in fertility both vary substantially in the course of this run.

We have made an initial foray into agent-based demography. The range of phenomena obtained is heartening. Clearly, this is a rich area and our efforts barely scratch the surface. With this first ingredient of the proto-history—sexual reproduction and endogenous population dynamics—in hand, we now proceed to the second, the formation of cultural groups.

Cultural Processes

Our simple agents may not yet seem quite human since all they do is move, eat, and procreate. In this section we give our agents internal states representing cultural factors and augment their behavioral repertoire with simple local rules for cultural interchange. This proves sufficient to produce agent populations having dynamic, heterogeneous cultures. Then, given that any two agents may be either similar or different culturally, it makes sense to talk about distinct cultural formations or tribes of agents. Indeed, we will "grow" such tribes here "from the bottom up."[15]

---

14. This is implemented by, among other things, having each agent keep pointers to all of its children.

15. Axelrod [1995] studies a bottom-up model of culture in which the agents maintain fixed positions on a two-dimensional lattice. Axtell *et al.* [1996] discuss an implementation of Axelrod's culture model in Sugarscape and the usefulness of such "docking" experiments for agent-based social science.

Cultural Tags

Recall that every agent is born with a genetic endowment: a metabolism, a vision, a sex, and so forth. Although the distribution of these genetic attributes changes from generation to generation, the genetic makeup of any particular agent is fixed over its lifetime. Of course, in reality, important attributes (for example, tastes) *do* change in the course of one's life.[16] We wish to capture processes of this sort. So beyond its fixed genetic endowment, each agent is born with a structure that represents its cultural attributes. This is a string of zeros and ones.[17] The length of this nongenetic string is the same for all agents.[18] For example, an agent might have a cultural string consisting of 10011010011. We will refer to each element of the string as a tag and will often call the entire structure a "tag string," or simply the agent's "tags." Agents can change one another's tags, which causes the distribution of tags in society to change over time.

Cultural Transmission

Consider an agent who has just landed at some site on the sugarscape. That agent—let us call her Rose—has up to four von Neumann neighbors (as discussed in Chapter II). For illustration, imagine she has two; call them A and B. Cultural transmission might proceed in a great variety of ways. We will adopt the following tag-flipping scheme. First, a neighbor is selected, say neighbor A. Then, one of Rose's tag positions is selected at random. Suppose it is position six and suppose Rose has a 1 at that position—a cultural tag of 1. Then, if neighbor A has a tag of 0 at that position (its position six), it gets flipped to Rose's value of 1. If, at that position, neighbor A already matches Rose, no flip occurs. Now Rose moves on to neighbor B. Again, one of Rose's tag positions is

---

16. In fact, there is a longstanding debate in economics as to whether or not preferences for commodities change during one's life. This is a topic to which we will return in Chapter IV, where we use the cultural exchange apparatus described here to model preferences that vary.

17. The idea that cultural attributes might be profitably modeled as if they were alleles on a cultural chromosome—called "memes" by Dawkins [1976: 206]—has been studied systematically by Cavalli-Sforza and Feldman [1981] and applied to problems of gene-culture coevolution, such as the lactose absorption problem [Feldman and Cavalli-Sforza, 1989]. Related work includes Boyd and Richerson [1985].

18. In the Sugarscape software system, the string length is a user-specified parameter. We have experimented with lengths from 1 to 1000.

selected at random. If, at that position, neighbor B already matches Rose, no change is made. Otherwise, neighbor B's tag is flipped to agree with Rose's tag at that position. Rose's turn is then over, and it is the next agent's turn to flip its neighbor's tags. A summary statement follows.

> <u>Cultural transmission rule (tag-flipping)</u>:
> - For each neighbor, a tag is randomly selected;
> - If the neighbor agrees with the agent at that tag position, no change is made; if they disagree, the neighbor's tag is flipped to agree with the agent's tag.[19]

Now, imagine that we start with a primordial soup of agents with random genetics, random tag strings, and random initial positions on the sugarscape. In the course of an agent's life, its movement, based on the sugar drive, brings it into the neighborhoods of all sorts of other agents, who may flip its tags, just as we, in the course of our lives, may be influenced—in our tastes or beliefs—by contact with other individuals.

Cultural Groups

Having fixed on a tag transformation rule, a separate issue is how to define groups. As usual, we choose to do it in a simple fashion.

> <u>Group membership rule (tag majority)</u>: Agents are defined to be members of the Blue group when 0s outnumber 1s on their tag strings, and members of the Red group in the opposite case.[20]

---

19. Many other cultural transmission rules are possible. An agent might flip *n* of its neighbors' tags, not just one, as above. Or, reversing roles, it could be neighbors who flip the agent's tags, *k* at a time. Or, agents and neighbors could *swap* tags, and so on. Eigen and Winkler [1981] have considered a variety of rules in the guise of "statistical bead games."

20. Many other rules for group membership are possible. One might identify particular positions—or sequences thereof—with certain groups. Tag position five might encode an agent's religion (0 for Muslim, 1 for Catholic). Group membership could require tag unanimity, with one tribe having all 0s and the other having all 1s. For tag strings of length 11, one three-group scheme is given below.

Agent Group	Number of Zeros on String
Blue	0 – 3
Green	4 – 7
Red	8 – 11

By increasing the string length and introducing considerations of tag ordering, very refined schemes become possible.

So, an agent with tag string 01010001010 would be a Blue, while one with 01001110101 a Red.[21] Since tag order is irrelevant here we might call this a "voting rule."

Notation

We have been denoting all rules with bold-faced letters (for example, **M** for movement). In principle, we could allot separate symbols for our cultural transmission (tag-flipping) and group membership (tag majority) rules. But, since we will only employ these rules together, we collapse them into a single symbol, **K**, which denotes this combination.

Cultural Dynamics

Recall that one component of the "proto-history" is the formation of spatially segregated, culturally distinct groups. Are the simple rules elaborated above *sufficient to generate* such outcomes? Returning to the familiar sugarscape, let us begin with a population of agents with random genetics, random tag strings each of length eleven, and random initial locations. The sugarscape grows back at unit rate. Agent movement is governed by rule **M** (each agent moves to the nearest unoccupied site having largest sugar within its vision and gathers the sugar) and sex is turned off. In the animations that follow agents are colored according to their group, with Blues colored blue and Reds colored red. A typical cultural evolution of this artificial society is shown in animation III-6.

The animation terminates with all agents Blue after some 2700 time periods. If, as in this run, the initial population segregates spatially—with separate subpopulations hiving separate sugar heights—then each such subpopulation will ultimately converge to pure Blue or pure Red.[22] Thus, **K** is *sufficient to generate* cultural groups.

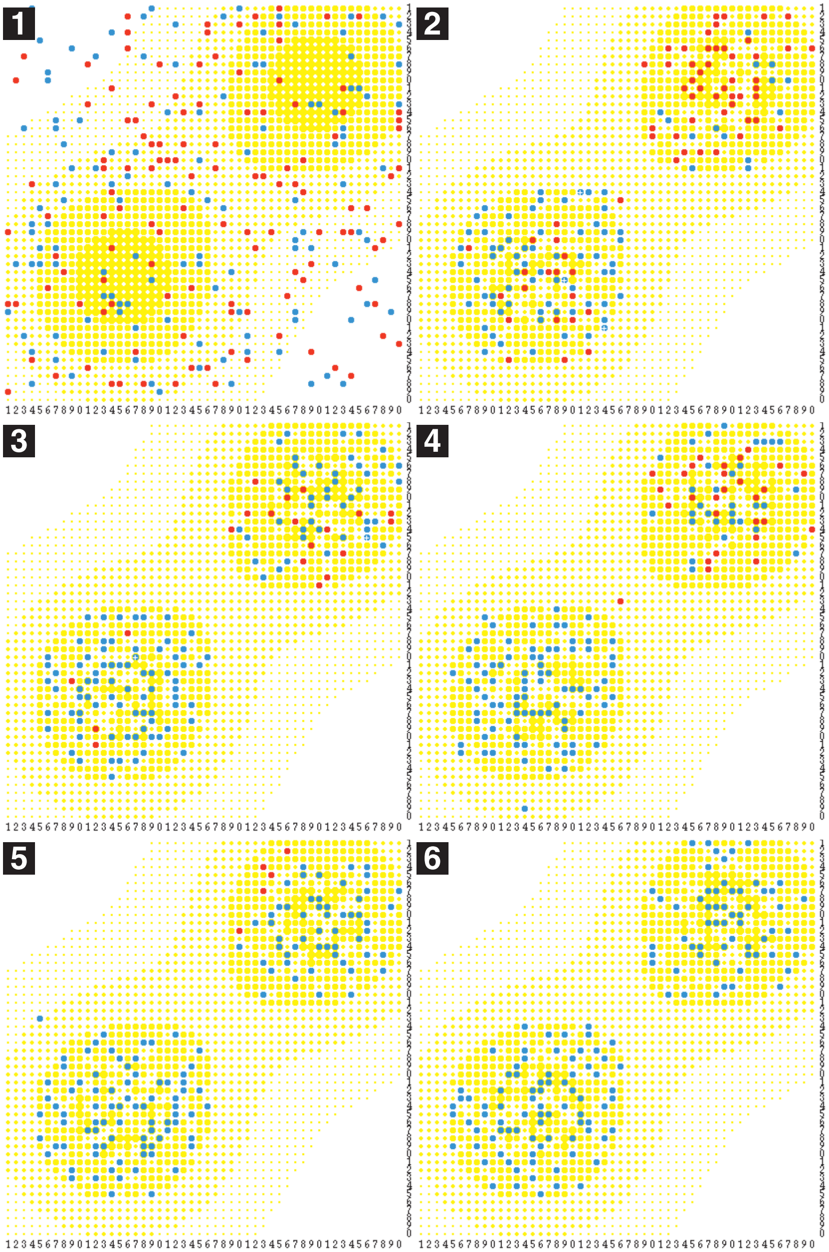
One way to monitor tag-flipping dynamics is to use a histogram displaying—at each time—the percentage of all agents having 0s at each

---

21. In order to keep this rule unambiguous the number of tags should be odd.

22. For a spatially segregated population engaged in cultural transmission according to rule **K** it can be shown that a monochromatic state is an absorbing state of the process. If some (small) rate of cultural tag mutation is introduced, then the system will hover near one of the monochromatic states, occasionally changing colors completely. Similar dynamics arise in a variety of contexts; see Arthur [1988, 1990], Arthur, Ermoliev, and Kaniovski [1987], and Kaniovski [1994].

Animation III-6. Tag-Flipping Dynamics under Rules ({$\mathbf{G}_1$}, {**M**, **K**})



Animation III-7. Tag Histogram Evolution under Rules ({$\mathbf{G}_1$}, {**M**, **K**})

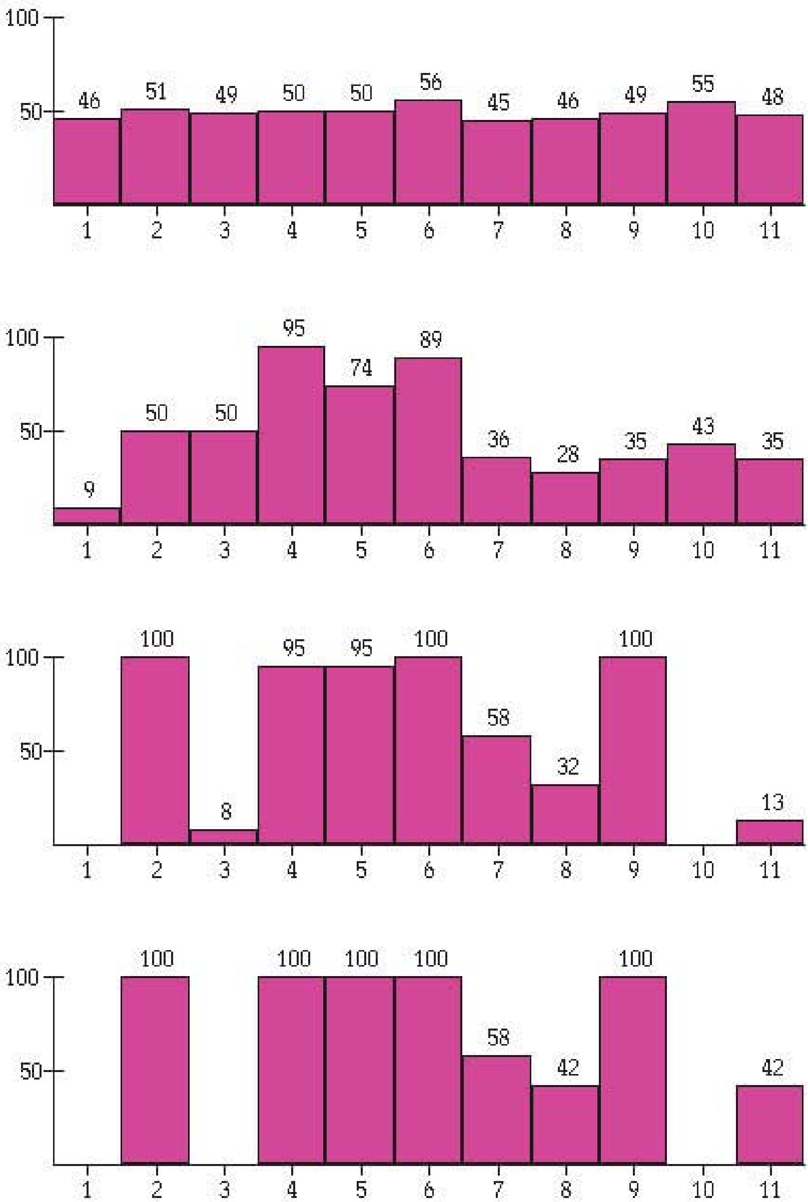
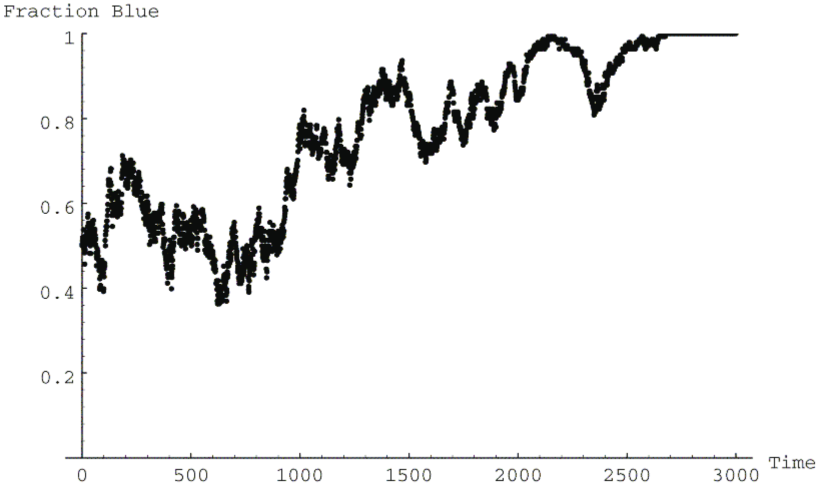


Figure III-8. Typical Cultural Tag Time Series Realization under Rules ({$\mathbf{G}_1$}, {**M**, **K**})



position on the tag string. Suppose we freeze such a histogram at some instant in the tag-flipping process, as shown in the first frame of animation III-7. The horizontal axis is divided into eleven bins, one for each tag position. The height of the bin gives the percentage of agents having a 0 at that position. So, in this example 49 percent initially have a 0 as the third tag of their string, 55 percent have a 0 as the tenth tag, and so forth. Of course, tag-flipping unfolds in time so the histogram is not frozen but evolves as the reader will see by running animation III-7. This dynamic histogram gives tag statistics obtained from the previous animation.

For some tag positions the percentage of all agents having a zero ultimately converges to zero (all agents have a 1 there) or one hundred (all agents have a zero there). Of course, once either of these "unanimous" states is reached, there can be no further tag-flipping since there is no tag diversity at that position. In short, there is "lock-in."

Figure III-8 shows a plot of the fraction of Blue agents over time. Note that long-run convergence to a single group need not be monotonic; wild fluctuations may occur en route to equilibrium. As the length of the cultural chromosome increases, so does the time required for convergence. Similarly, adding agents increases convergence time.

Now, two individuals might each consider themselves "American" culturally, while differing politically, religiously, or in other respects. An interesting feature of this agent group membership rule is that agents can be very different culturally, measured position-by-position, and yet be members of the same group. To see this consider two agents having tag length five. Suppose the first has tag string 00011 and the second has tags 11000. These two agents have but a single tag in common, the third one, and yet they are both Blue since 0s predominate. All agents can be the same color (as in figure III-8) *without* being culturally identical. A corollary of this is that a pair of Blues can produce a Red agent. How can this happen? Imagine a Blue agent (who is the flipper) and a Blue neighbor (the “flippee,” as it were) with the following tag strings of length five:

Agent’s tag string	10100	Blue
Neighbor’s pre-flip tag string	01010	Blue

Each is Blue since 0s outnumber 1s. But suppose “God” (the random number generator) picks tag position three. Since the agent has a 1 there, it flips the neighbor’s tag to 1 at that position, resulting in the neighbor’s new tag string: 01110. But now 1s outnumber 0s, so the neighbor turns Red! Once more, a simple rule—here the tag-flipping rule—produces interesting results.

Ultimately, we want to have cultural transmission operational at the same time the sex rule is active, so we need some way to specify the state of a newborn child’s cultural tags. The transmission of cultural attributes from parents to children is termed *vertical,* as against the *horizontal* transmission we have been discussing.

Vertical Transmission of Culture

When sex rule **S** is active, a child’s tag string is formed by comparing the parents’ tags at each position and applying the following rule: If the parents have the same tag (both have 0 or both have 1), the child is assigned that tag. If, however, one parent has tag 0 and the other has tag 1, then we “toss a fair coin.” If it comes up heads, the child’s tag is 1, if tails, it is 0. All of this is summarized in table III-2.[23]

23. Those with a background in population genetics will notice that this is strictly analogous to a random mating table for one locus with two alleles.

Table III-2. Probability That a Child Receives a 0 or 1 Tag When Born, Based on the Parents' Tags

	Probability that a child's tag is	
Parents' tags	0	1
Mother 0, father 0	1	0
Mother 0, father 1	1/2	1/2
Mother 1, father 0	1/2	1/2
Mother 1, father 1	0	1

This procedure is applied at each position, resulting in a cultural endowment—a tag string—for every newborn child. Of course, once the child is out on its own all agent behavioral rules apply, including **K**. Thus horizontal transmission will soon modify the child's initial, vertically transmitted, tags.

Networks of Friends

In Chapter II we defined agent neighbor networks and showed how these change over time. Earlier in this chapter we displayed genealogical networks. Here, given that the agents are flipping tags with their neighbors as they move around the sugarscape, a natural notion of "friendship" arises. Agents who at some point are neighbors and are close culturally are defined to be friends.[24] When an agent is born it has no friends. However, in moving around the landscape it meets many agents—as neighbors—and interacts with them culturally. Those agents with whom it interacts and who are closest to it culturally are ones it remembers as its friends.[25] Then, if one draws lines between friends, one has a friendship network.

To implement this in Sugarscape, we employ the Hamming distance to measure the closeness of cultural tag strings.[26] Each agent keeps track of

24. We offer this definition of "friendship" as a simple local rule that can be implemented efficiently, not as a faithful representation of current thinking about the basis for human friendship.

25. In the agent object this is implemented as a pointer to the friend agent (see Appendix A for more on the object-oriented implementation of the agents).

26. The Hamming distance between two (equal length) binary strings is obtained by comparing the strings position-by-position and totaling the number of positions at which they are different. Therefore, two strings having a Hamming distance equal to zero are identical.

the five agents it has encountered who are nearest it culturally; these are its friends. Each time an agent encounters a new neighbor the agent determines how close they are culturally and, if the neighbor is closer than any of the agent's five friends, the neighbor displaces one of them. Drawing connections between friends yields the network shown in animation III-8.[27]

Many variants on this general idea are possible.[28] For instance, instead of connecting all friends one could draw lines only between *mutual friends*; that is, a line would connect agents A and B only if A considers B as a friend and *vice versa*. Another variation would be to connect only *best friends*; that is, A must consider B to be its best friend—closest culturally—and B must think the same of A. Finally, note that whether two agents are friends or not has no effect on their behavior. In this sense the network of friends is *external* to either the cultural exchange process or the friend assignment rule. A natural extension of the "network-of-agents" concept would be to permit regular agent-agent interaction over such networks, reinforcing positive interactions and perhaps breaking connections as a result of negative interactions, a kind of Hebbian picture.[29] In this way the networks take on a feedback flavor; interagent cultural transmission begets networks of friends, which in turn modify the transmission dynamics.

Networks such as those we have described manifest themselves in the real world in many important ways. Politically, restrictions on freedom of assembly, freedom of speech (press censorship), and freedom of movement (internal passport requirements) are standard tactics of repressive governments. The main aim of these measures is to keep individual dissenters—of which there may be a great many—isolated from one another, to keep them from *connecting* with other dissenters, and so

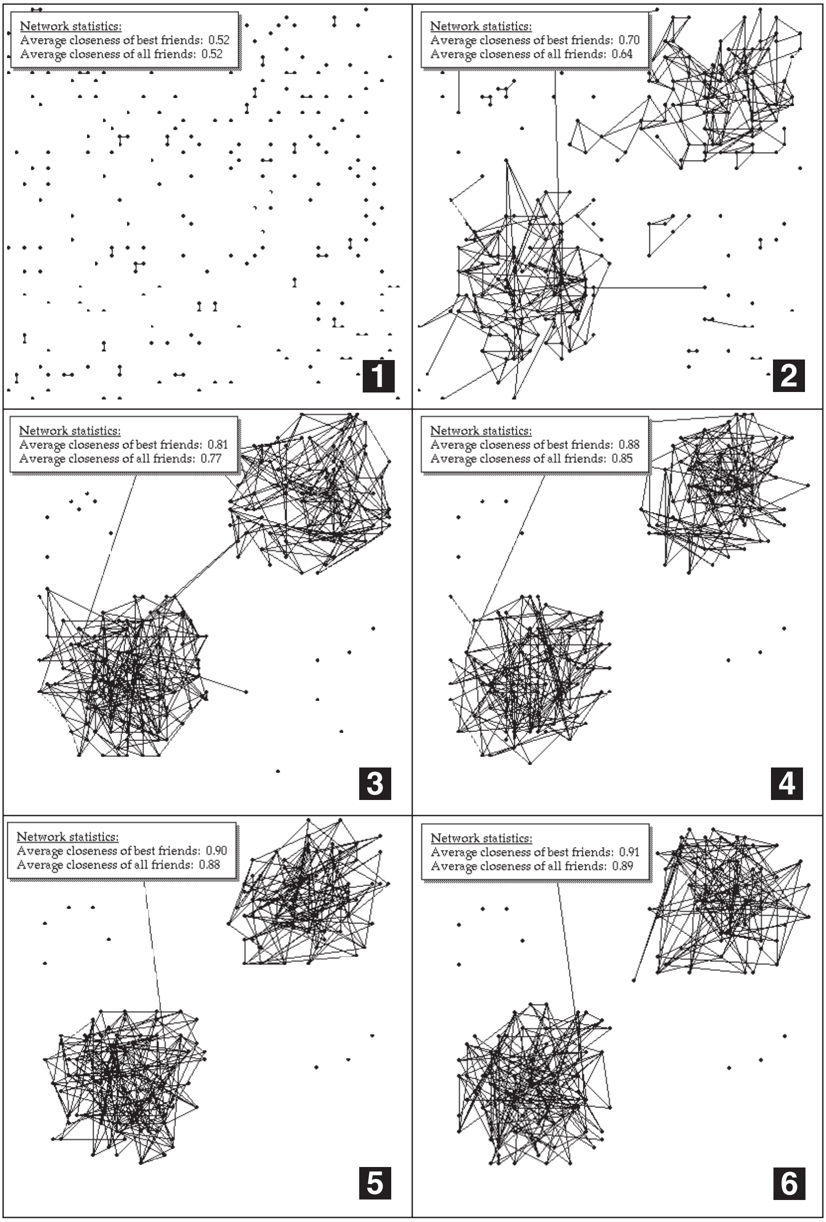
---

27. Occasionally a line across the entire lattice is observed. Since the sugarscape is a torus, an agent at the extreme left of the lattice may be a friend of an agent at the extreme right, yielding a friend connection line that spans the entire lattice.

28. There are actually two distinct ways to keep track of friends, producing somewhat different pictures. In animation III-8, once an agent stores another as its friend it never checks to see whether or not the agent continues to be close culturally once the two agents cease to be neighbors. That is, the agent's list of friends can become highly anachronistic as both it and its friends engage in cultural exchange over time. An alternative way to implement friends would be to keep updating the cultural closeness of friends each time period, although this would involve spatially nonlocal communication.

29. Recently Holland [1993] has studied the effects of tags on social interactions in an agent-based model.

Animation III-8. Evolution of a Network of Friends under Rules ({$\mathbf{G}_1$}, {**M**, **K**})



to thwart the emergence of an organized *community* of dissenters, conscious of their numbers. How do changing political borders and "information revolutions" (for example, the Internet) affect the emergence of groups? How does "samizdata" spread across a landscape? Artificial societies allow us to study such questions systematically.

Now that rules for sexual reproduction and cultural exchange have been elaborated, let us turn to combat.

Combat

The cultural processes described above have proved *sufficient to generate* tribes—distinct cultural formations of agents. In this section we permit combat between agents from different tribes.[30] We do this by modifying the movement rule.

Specifically, imagine being a Blue agent. And suppose that within your range of vision there is a lattice position of sugar height 3, and that there is a Red agent sitting at that position. Then, if you take over that position, you take in the 3 sugar units *plus some additional reward from preying upon the Red agent*. One possibility is that you get the total accumulated sugar wealth of the agent. Or you might get a flat reward of, say, 2 sugar units. In the latter case, the full value of taking over the position would be 3 + 2 = 5 sugar units. We will examine both types of reward rules. First, however, we need to establish reasonable conditions under which agents can prey on members of the opposite tribe.

To begin, it does not seem plausible that a "tiny" agent (one with little accumulated sugar) should be able to prey on a "huge" agent (one with vast accumulated sugar). At a minimum, then, we require that the predator be bigger than the prey in terms of accumulated sugar. It turns out that, to produce interesting dynamics, something more is required. In particular, if you are a Blue agent then you can plunder a Red agent—call him Rollo—only on two conditions. First, you must be bigger than Rollo. But second, there must be no other Red agent within your vision bigger than you will be after you defeat Rollo. In that case, we *define* the attack site as being *invulnerable to retaliation*. This second requirement provides

30. For an interesting discussion of tribal warfare from an anthropological perspective, see Ferguson [1992].