Part II

Animacy [Action Agents]

Periodic, cyclic behaviors are universal among all living systems. At short time scales, cells pulsate, organisms breath and palpitate, hearts beat, creatures walk, swim or fly. Classical cybernetics regards these activities as oscillators with feedback control mechanisms. In the more complex systems, there is typically a hierarchy of control. Cognitive capabilities are often assumed to emerge from this complexity.

Anigrafs explores another possibility: the control of periodic activities are exercised via rudimentary mental organisms. Each mental organism is associated with its own mechanism that initiates a particular act or behavior. Although these acts may be reflexive, like a knee-jerk, we infer there are agent-like daemons who activate them. The set of these agents thus represents a distinct level of description, being part of a less confined, social control network that decides just how the system should behave. For this abstraction to be plausible, there must be a competition for control. The next few sections show that in the presence of such competition, periodic behaviors are possible even for very simple organisms. These "social control mechanisms" distinguish themselves by not requiring classical cybernetic governors.

24 Jul 07

Anigraf 1: Cells & Cycles
a breath of life

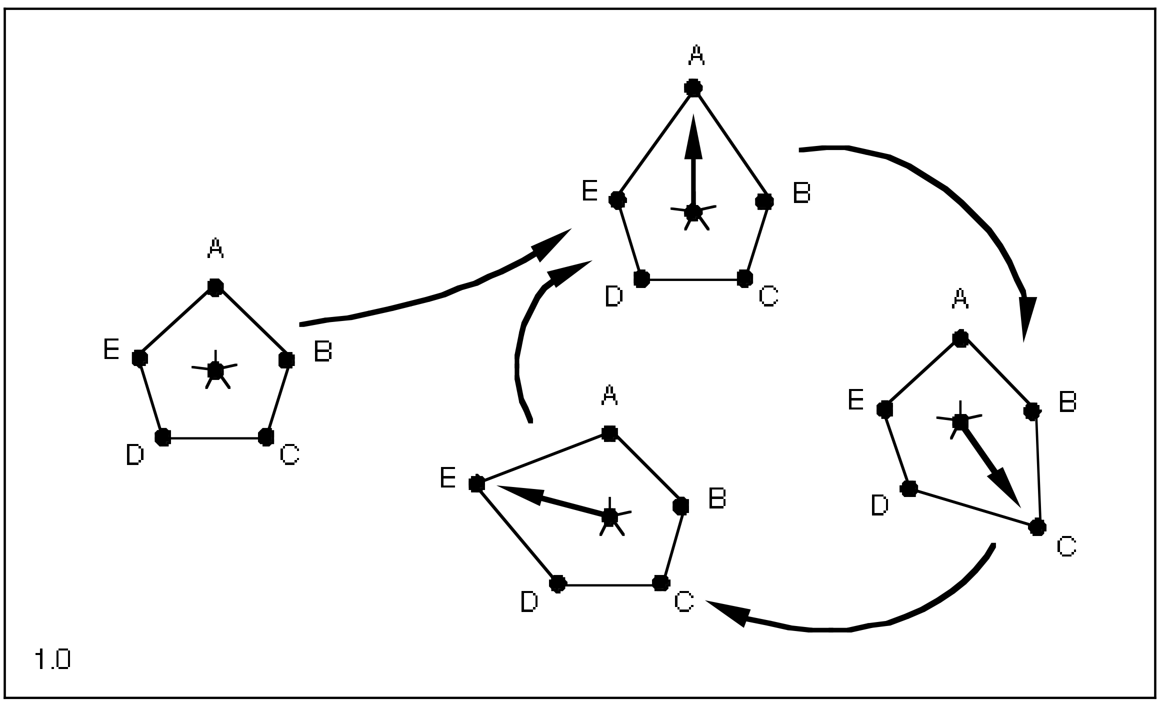

Fig 1.0. Characterization of pentagonal distortions arising from cyclic Condorcet outcomes.

1.0 Bridging Cells and Societies

An obvious assertion is that the evolution of mental organisms parallels their biological counterparts. Mischievous Daemons seem plausible only for higher forms of life, whereas assigning mental attributes to single cell creatures with reflexive behaviors seems quite implausible. Nevertheless, if even the most simple animate systems are capable of a variety of behaviors, different mechanisms must underlie each of these actions. A competition for control then emerges: which of the several possible actions should the anigraf system elect? The designs of the machinery for making such categorical choices will be quite different from those that implement actions of body parts. The anigraf captures the basic structure at this other level, of decision-making. The aim is to make explicit how choices for actions are related and reached. The abstraction allows us to view mental organisms not only as modules of a brain, but also as distinguished components of very simple cellular systems.

Let us use the more neutral term "agent" to describe the operator that controls the state of a physical actuator in a simple system. Each actuator initiates an action or behavior that moves the system closer to a particular goal state, which is the goal sought by its controlling agent. In the left panel of Figure 1.1, we have five goal states [P,Q,R,S,T]. Associated with each goal is an agent and an actuator. The graph shows how the goal states are seen as related by the organism under consideration. Although one might attempt to capture these same relationships as parts of each actuator, such a model would confuse the two separate levels of description we wish to separate: the level of the physical mechanism vs. the level of the relations between the types of actions effected by these mechanisms. In our simple example, we illustrate with two different groups of agents – one "male", the other "female" - both of which have the same goals and actuators. The male organism relates the five behavioral acts as a triangle with a tail, whereas the female sees the goal states as related by a pentagon. These are but two of the twenty-one possible 5-agent organisms.

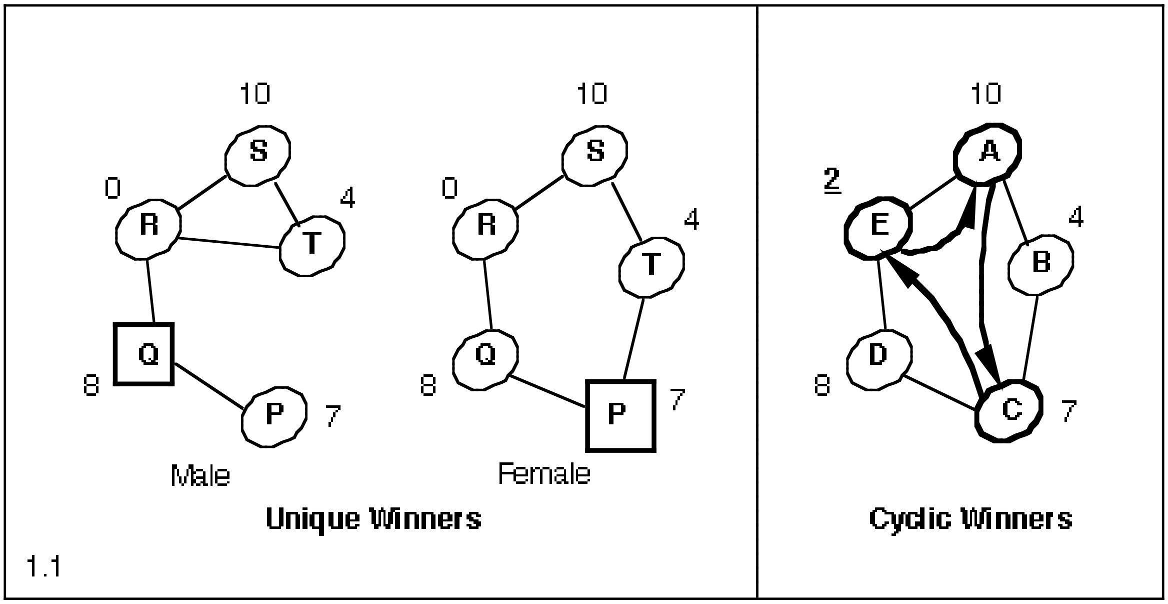

Fig 1.1 Left panel illustrates two anigraf forms, with the same weights on corresponding nodes. In the right panel, the weight on node R of the "female" anigraf has been diddled slightly. The other weights remain as before. Without any further change in weights, the new outcome is the cyclic sequence A,C,E,A,

How will these two graphical forms affect the choice outcomes? Note that both have identical desires of their agents, as shown by the weights next to the labeled nodes. Using the optimal Condorcet pair-wise tally (see procedure in earlier chapter), we find that the male organism will choose action Q, whereas the female's choice is P. Not surprisingly, the form of the similarity relations among agents depicted by the anigraf plays a major role in controlling the behaviors of not only complex societies, but also of simple, cellular-like organisms.

1.1 Dynamics

Even the simplest living systems exhibit periodic activities, such as pulsation, which can be driven solely by internal forces. Can our small society of anigraf agents do likewise, without invoking classical, homeostatic feedback control mechanisms? If so, then this kind of cyclic activity should occur without any changes in the strengths of the agent's desires, and result simply from the properties of the state and structure of the social network. Clearly, if the aggregation of the agents' whims always yields a unique winner, then only one action ensues. Hence tally procedures such as Plurality, Top Two, or Borda described earlier are not appropriate. However, if agents conduct Condorcet tallies using pair-wise comparisons, then cycles among choices are possible. Specifically, selected weights on anigraf nodes can trigger a sequence of actions, without any change in these weights. Such a dynamics allows anigrafs to emerge from simple cause-effect, feedback-type reactions to behaviors with a more choreographed repertoire of actions.

The pentagonal anigraf at the right of Fig 1.1 illustrates how cycles in outcomes can emerge. This anigraf [A….E] is identical to the adjacent "female" pentagonal anigraf [P….T] in the left panel. The only difference is a very small change in one of the input weights: Agent E has weight 2, rather than the 0 weight held by the corresponding agent R. Because we might expect the small weight change to have little consequence, the likely winner in anigraf [A…E] is node "C", which is comparable to the previous winning node "P" in the female anigraf [P…T]. Indeed, as shown in the first rows of table 1.1, C does beats A, B, and D in pair-wise contests. However, C fails to beat alternative E (fourth row.) As we continue to examine the remaining pairs, we see that A will beat E, and so will B and D beat E. Hence there is at least a three-cycle among pair-wise comparisons: A beats E which in turn beats C, which now beats A. Although there has been no change in the weights on

Table 1.1 Pair-wise Condorcet Tally (Pentagon)

Pairs	A(10)	B(4)	C(7)	D(8)	**E(2)**	Total	Winner
AvsC	10	0	-7	-8	2	-3	**C**>A
BvsC	10	4	-7	-8	0	-1	**C**>B
CvsD	0	4	7	-8	-2	+1	**C**>D
CvsE	-10	4	7	0	-2	-1	**E**>C
AvsB	10	-4	-7	0	+2	+1	**A**>B
AvsD	10	4	-7	-8	2	-1	**A**>D
AvsE	10	4	0	-8	-2	+4	**A**>E
BvsD	10	4	0	-8	-2	+4	**B**>D
BvsE	0	4	7	-8	-2	+1	**B**>E
DvsE	-10	0	7	8	-2	+3	**D**>E

nodes, at each time click, one of these choices will dominate the cycle and the behavior of the system will be perturbed. Such perturbations might, for example, effect a change in shape of the physical system. Cast as one of Braitenberg's little vehicles resembling a pentagonal cell, we would have a sequence of distortions such as those depicted on the front panel (Fig 1.0). These dynamics would continue until a new set of weights were introduced.

Definition*: A* ***top-cycle*** *among alternative choices occurs when there is an alternative a_i that beats a_i, a_i beats a_k, and a_k beats a_i, and every alternative not in the top-cycle is beaten by at least one alternative in the top cycle.*

Note that a Condorcet tally must lead to a top-cycle if no alternative beats all remaining alternatives in the pair-wise comparison, excepting ties. Furthermore, if there is a top-cycle in the outcome, then there must be at least a three cycle, such as the example given above. Top cycles add a dynamics that will play an important role in the behaviors that follow.

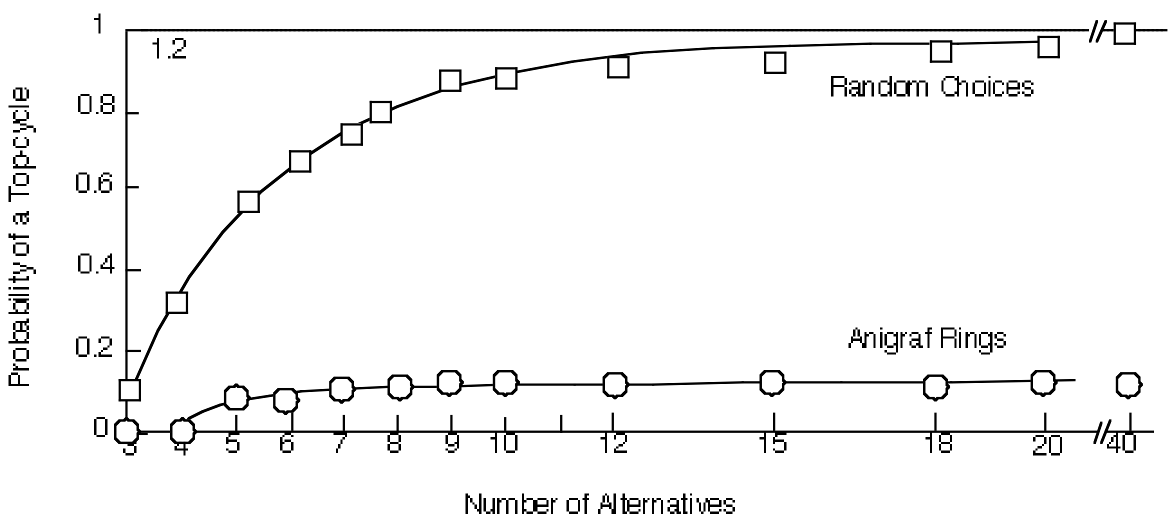

Fig 1.2. Let weights on nodes be chosen from a uniform distribution. If the anigraf form is ignored, then probability of top cycles rises rapidly as the number of alternative increases (top curve.) In contrast, if the anigraf form is respected when a tally is conducted, the probability of top cycles can be controlled (bottom curve.)

1.2 From Cycles to Chaos

Cycles are typically a prelude to chaos. There are two obvious ways to create chaotic sequences of outcomes. The first, and more difficult, is to choose appropriate weights on special graphs like the pentagon. A second method, much simpler, is allow agents to vote haphazardly, ignoring the relations among choices specified by their anigraf. Fig. 1.2 illustrates this second case. Note that as the social system becomes larger and larger, cyclic outcomes become more and more likely, with 1 as the asymptote. The probability of top cycles is already 2/3rds for 6 agent systems and for a group of twelve agents, 90% of the weights on nodes that reflect agent desires, will result in a top cycle among the choices. If now these weights are perturbed slightly from tally to tally, the result is a chaotic sequence of outcomes.

To introduce controlled behaviors with less likelihood of a chaos of cycles, agents' preference rankings must respect the anigraf form. But this, in itself is still not sufficient. Consider the ring anigraf as illustrated earlier by the

Why Chaos ?

To provide some insight into why chaos, we need a more detailed analysis of the relationship between the preference orderings and the calculation of pairwise winners. The functions of interest are an expansion of the set of pairwise outcomes [n|2] in the n unknown weights for the agents. If each pairwise comparison is independent of another, as it would be for random weight choices, then there will be [n|2] equations in n unknowns (the weights of n agents.) The random assignment of weight to each row provides ample opportunity for finding at least one case where any agent will be beaten by another in the pairwise comparisons. Hence there will be no Condorcet winner, and cycles in outcomes emerge (Saari, 1998.)

pentagon. The lower curve in Fig. 1.2 shows that as ring size increases, so does the likelihood of top cycles, At worst, the top cycle will occur for about 12% of the weights on nodes that reflect the desires of the agents – assuming these weights are chosen from a uniform distribution. In general, if top cycles are desired, then some non-arbitrary weights will be required. Other simple anigraf forms that can lead to top-cycles are shown in Fig 1.3 (left). Whenever these forms appear as components of an anigraf (e.g. an induced ring or induced "house"), top-cycles in outcomes may occur -- although the probability of encountering a top-cycle is typically much less than for a ring anigraf.

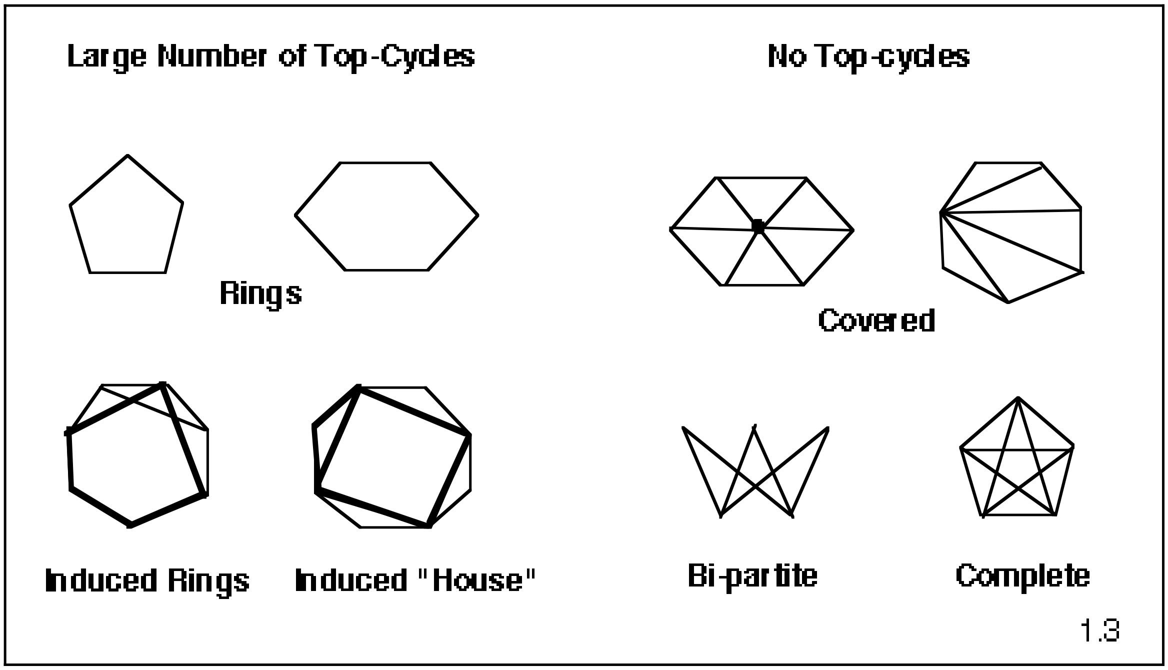

Fig. 1.3. Graphical forms such as rings or a house can support top-cycles (left.) However, other forms such as those illustrated on the right, have unique winners regardless of weights on nodes.

One might now wonder whether there are graphical forms guaranteed never to have cycles. The answer is ***YES***, provided that agents discriminate all choices in the Condorcet pair-wise comparisons. If the anigraf network is completely connected or is "covered" (one node is adjacent to all others), or is equivalent to a complete bi-partite graph, then there will be no Condorcet top cycles given that each agent's preference orderings are consistent with the graph structure. Other examples are shown in the right panel of Fig 1.3. These "stable" Anigraf forms can be contrasted with those having a high probability of top-cycles, as shown in the left panel. Note that the addition or deletion of a single link in the network can cause significant changes in whether the social system can easily reach a unique consensus or not. The connectivity of the network thus plays a key role in the potential for cyclic outcomes.

1.3 Summary

Anigrafs have a wide range of potential behaviors, ranging from unique, stable outcomes (87%) to chaos when the Anigraf model relating alternatives is ignored. For stable outcomes, an agent or mental organism's ranking of choices must be consistent with the anigraf form that relates these choices. This form represents the shared, or common intrinsic knowledge about the choice domain. Of special interest is that about 12% of the time, non-chaotic cyclic outcomes can happen for certain choices of weights, even when the anigraf form is respected and neighbor-only communications are in effect. In these cases, the tally machine will deliver a cyclic sequence of outcomes until new weights are entered. Even with random weight selections for agent desires, this behavior occurs with a level of significance that provides some simple anigrafs, such as rings and later, also chains, with the potential to achieve pulsating or rhythmic activity typical of very simple animate cells. In contrast with classical control systems, here it is not a physical feedback mechanism that underlies the cyclic sequence, but rather the manner in which information is shared: who talks to whom about the preferred next state for the system as a whole.

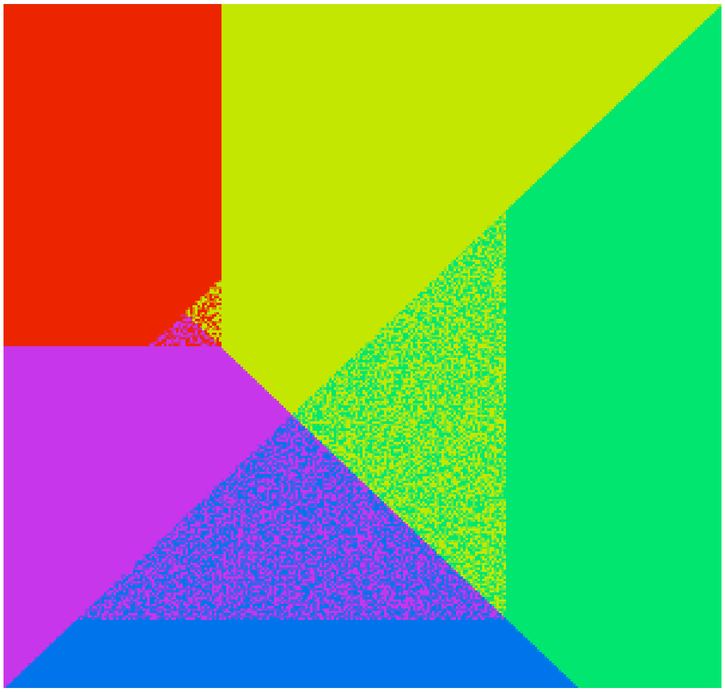

Plate 1: Phase Plot Showing Winners for a House Anigraf with weights (6, 3, x = 0-10, y = 0-10, 1). Vertices labeled clockwise beginning with tip of roof. Textured areas are topcycles. (T.J.Purtell, 2004)

2. Anigraf2 : Swimmers
beginning to move

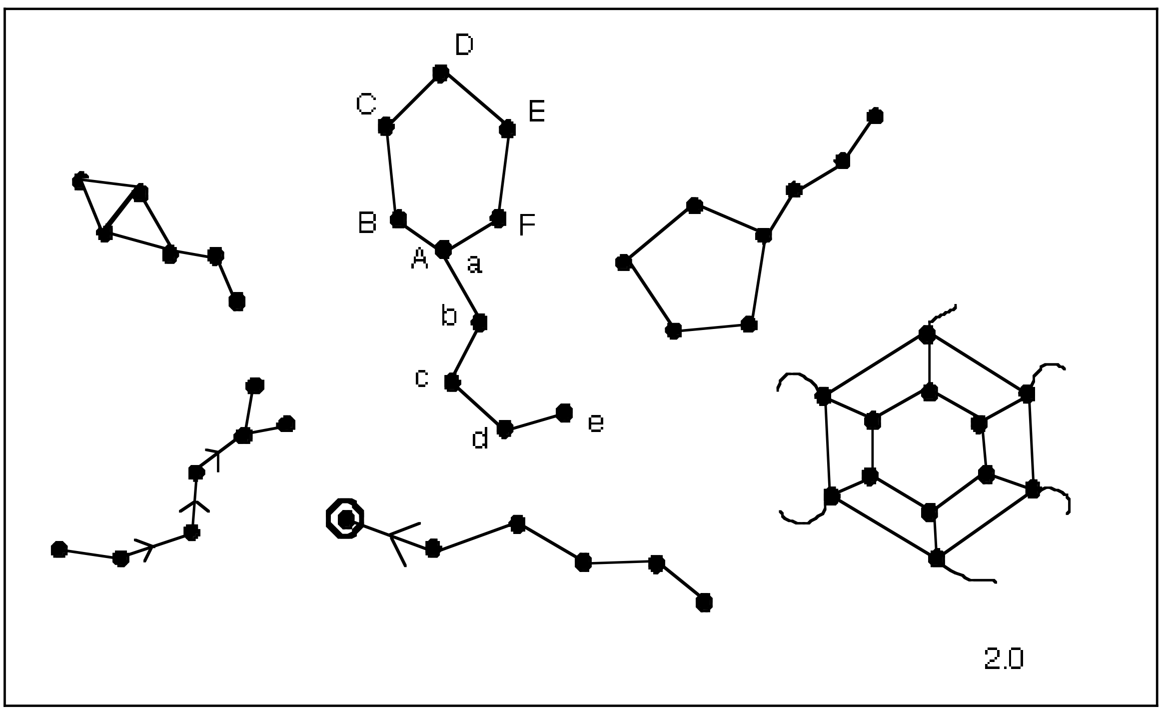

Fig. 2.0 A collection of anigrafs, some with directed edges, another with filia appendages.

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2.0 Movement

Cell Anigrafs had very limited behaviors, constrained for didactic purposes to simple ring forms. This simplification hid the potential complexity of designs and behaviors that could be attributed to primitive life forms. Here we begin to expand this repertoire. As before, we assume that the component mental organisms, or “agents” will have access to different kinds of interfaces to the environment, with interface hardware that affects the behavior of the system as a whole. Agents will have control over those interfaces, and will “vote” for the opportunity to exercise this control, depending upon the strength of its desire to achieve a preferred goal. In effect, then, we are formalizing a two tier system: one where the interface agent constitutes a member of the social system of all other agents, and another, lower level where each agent has its own sensory input and controls its own effector. However, the activation of the effector can occur only when approved by the society of all agents.

One of the most visible and prevalent effectors are flagella or hairy muscular fibers. For example, the single-cell Euglena has a flagellum that propels the creature forward. Another simple creature, the paramecium, has a host of hairy superficial fibers that can generate wave-like motions. These appendages can be entirely passive, with the movements initiated only at the point of attachment to the cellular body. More complicated limbs may have additional agents confined to “local” social enterprises that control special sinusoidal motions, such as the movement of wings, fins, legs, and eventually fingers. We begin first, however, with a description of a society of agents that can generate chaotic-like flagellations typical of coelenterates. This little society has simple objectives: to move one way or another.

2.1 Jellyfish

Coelenterates have very primitive neural nets that lie on the rim of a funnel-like body. When activated, this network causes a wave-like motion of tentacles attached to nodes on the rim. The jelly fish is an example. It has an inverted cup-like form with many tentacles emerging from the rim of the cup.

Typically the neural elements embedded in the ring appear in multiples of four. Each neuron drives its own tentacle, causing it to flagellate. The anigraf analog is thus a group of agents linked together in a ring-like configuration, such as those illustrated in Fig. 2.1. Of primary interest is how likely this type of anigraf will generate cycles among actions initiated by the constituent agents.

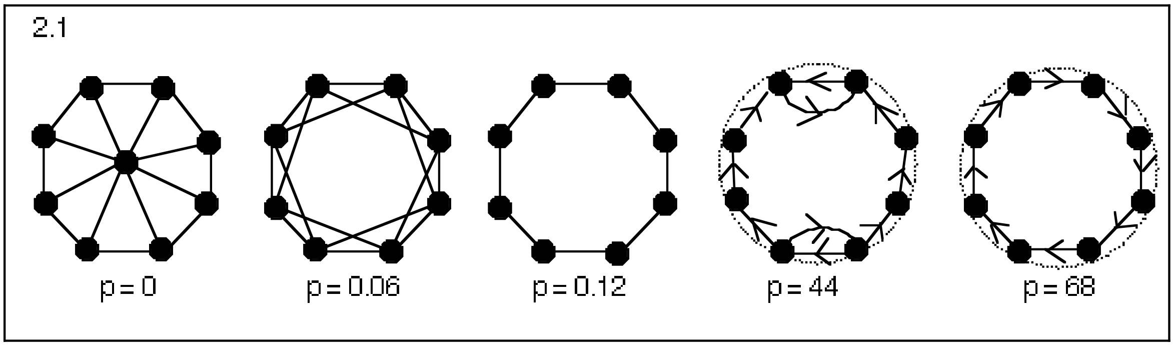

Fig. 2.1. Various anigraf ring-forms. The probability of a top cycle is shown below each, assuming that weights on nodes are taken from a uniform distribution, and Kd=2. Arrows indicate directed communications, or equivalently, weights added to one node but not vice versa.

If the anigraf form is a simple ring with bidirectional edges and Kd=2, then each agent communicates only with its two neighbors. The probability of cycles was shown previously to reach a peak at 8 - 12 agents (Fig 1.2.) Let us then consider design possibilities for an octagonal jellyfish anigraf, recognizing that both cyclic and non-cyclic outcomes are useful. An example of a cyclic outcome would be a top cycle that moved from one agent to another, rotating around the ring, and hence initiating a circular wave of activity. A non-cyclic outcome, on the other hand, might result in the coordinated constriction of the rim of the coelenterate as it captures a food particle.

Figure 2.1 shows a few modifications of the simple ring, and the probability of top cycles among outcomes using the Condorcet tally, where the weights on nodes (i.e. the strength of the agent's desires) are chosen from a uniform distribution. If the ring is reconfigured to "wheel", then the anigraf has one vertex that is adjacent to all others (i.e. the graph is "covered") and there will never be cycles (p = 0.) The next configuration is a regular graph, where each node has a degree of four. The top-cycle probability is about 6%, which is roughly half the cycle probability of the simple ring. Unfortunately, none of these percentages may be high enough to insure that our jellyfish can easily engage in complex, long-cycle flagellated movements.

A simple modification of our communication channels solves this problem: make the communication channels directional. In other words, let the weights of preferences be "passed on" from one agent to the neighboring agent, but not vice versa. Depending upon the directionality of the communication channel, we also will have the great advantage of being able to enforce either clockwise or counter-clockwise cycles among the rim agents. For the jellyfish with a ring of eight agents, clockwise, directed communication will produce clockwise cycles 68% of the time; for a ring of twelve agents, the cycle probability rises to 80%. These numbers are approximated very closely for $n > 4$ by cycle percentages shown earlier for random preference orderings. (See also Fig. 2.3.) The difference, however, is that a shared (directional) anigraf model is respected by all agents when ranking their preferences. Clearly we have the beginnings of a social control system that mimics a physical feedback controller, but here the condition of sharing social preferences is met.

A periodic wave of tentacle movements is but one of several actions that the jellyfish might engage in. Even if the agents all have identical effectors, all effectors need not perform identical movements, and consequently, all agents need not have identical goals for the system. Some agents might prefer that the jellyfish move to another, more favorable region in its environment (more "food" or perhaps "less hostile".) Another might want to ingest nutrients, another might wish to release a toxin. As in our primitive cell Anigraf1, some of these actions might entail a change in shape -- perhaps to be carried out by activating other internal fibers or membrane properties. In a very simple scenario, there could be two types of agents on the coelenterate's ring network, X and Y, where X agents would create an inward current and Y agents would create outward currents, or tighten the membrane supporting the ring. All these choices entail societal consensus that is reached after conducting the Condorcet tally among the agents. This coelenterate ring of agents can easily be regarded as a very primitive brain.

2.2 The Flagellum

Consider next yet another primitive creature, such as the sperm cell or Euglena, where a single flagellum controls movement of a simple, cell-like "body." If this appendage itself is passive, driven by forces applied to its base, the effect will be as if someone were whipping or twirling a cord. Such a cord will have some kind of natural frequency of motion when torques are applied at one end. As shown by Berg(1996), these simple creatures have a micron-sized motor that whips the miniature tail. Referring to Fig. 2.2, let's say agent **A** is responsible for initiating movement of this flagellum, thus satisfying an exploratory need to move forward. Then we know from Table 1.3 in the previous chapter that if voting strengths of the agents are suitably chosen,

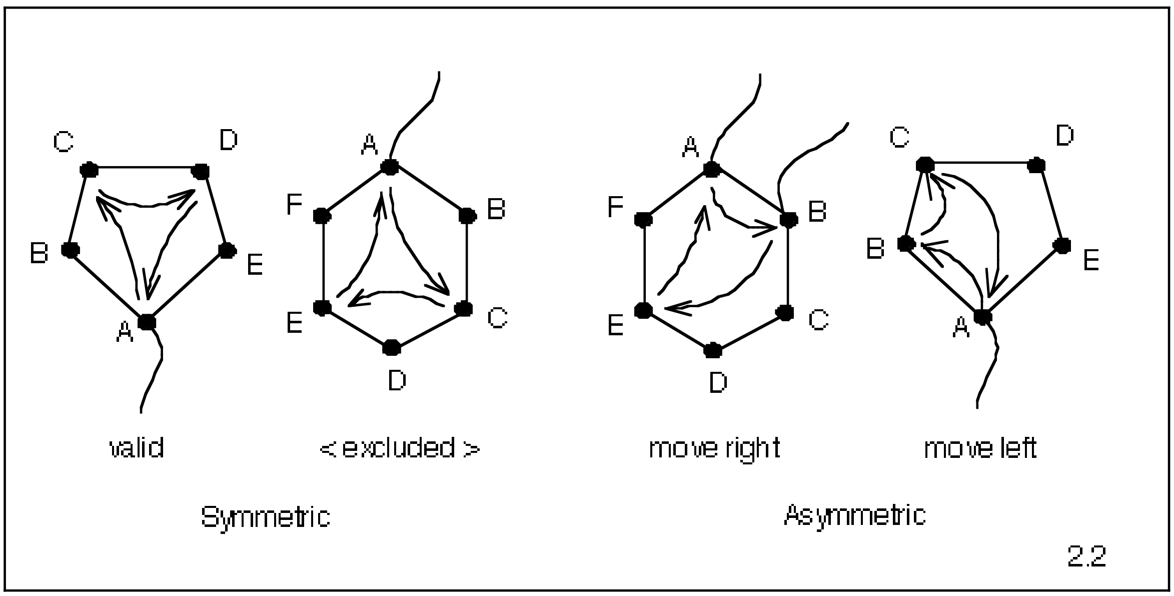

Fig. 2.2. Variations of cyclic outcomes for pentagonal and hexagonal Euglena. For rings with even numbers of nodes, there are restrictions on possible cycles.

cyclic outcomes will occur that will include agent **A**'s preference for system behavior. The little creature continues to flagellate until new voting strengths are tallied.

A variety of cycles that include **A** are possible for our Euglena. A few are illustrated in Fig. 2.2, including one that is excluded. Surprisingly, symmetric cyclic patterns are not possible for any ring anigraf with an even number of nodes, and bi-directional edges. Hence our hexagonal (or octagonal) Euglena must be content with asymmetric cyclic patterns, as shown on the right. Symmetric top cycle activation of agents about the tail node seems the most obvious choice for forward movement, whereas asymmetric cycles offer an option for changing the directions. Our hexagonal anigraf must thus use a zig-zag strategy for forward motion. Whether or not both members of a symmetric top cycle are adjacent or non-adjacent to **A** may also have consequences. For example, when neighbors of A are part of the top cycle, then agents such as C and D in the pentagon, or C and F in the hexagon, are free to reinforce each other's goals. A further, perhaps unforeseen, benefit of including agents nearest to **A** is that there is a 10 fold greater possibility of top-cycle activity. Clearly, even for our little anigraf Euglena, many different movements seem possible, capable of supporting a variety of behavioral goals. For eight node rings, the possibilities jump 5-fold.

2.3 "Smart" Tails

To create creatures with more complex locomotor abilities, we may wish to control the amplitude or form of the wave of the tail, or bias its body angle to change heading. These effects cannot be accomplished easily by a single, simple agent at the point of attachment of a passive appendage. Let us then break the tail into segments, simultaneously creating a chain of agents, each of whom controls the activation of one segment. Let one of these agents, say **A**, be selected as the "head", using bold upper case to make this designation. (Fig 2.3.)

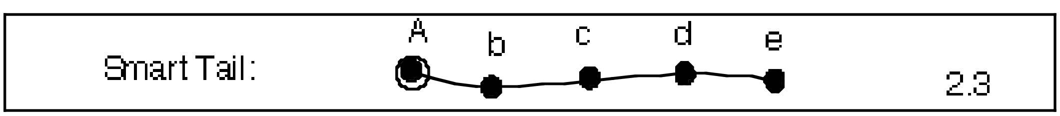

Fig 2.3. A 5-chain appendage, with node **A** designated as the head.

Because a chain is just a broken ring, the top cycle behavior of chains is very similar to that of rings, provided the agents only communicate with their neighbors (i.e. Kd = 2.) Our objective is to create a cycle of activity over one part of the **A,b….e** chain. In turn, this cycle among agents will effect a physical movement of the tail or body, such as when a fish swims or a snake crawls. We assume that the agents are embedded within a flexible shell that contains contractile tissue such that when an agent is active, muscular springs will contract to create part of a wave motion. A cycle among agents, say agents **A, b, d** or **b, c, e** can drive this kind of behavior.

It is easy to show that if there is no sharing of information between agents, then there can be no cyclic behavior. Intuitively, if all agents are independent, then in a pair-wise competition among choices, the agent with maximum clout will win. Similarly, although less obvious, if all agents share make distinction among all alternatives, and consequently place a preference ordering on all alternatives, then again there can be no cyclic behavior. (Black, 1958; Richards et al, 2002.) Cycles among agent choices are most likely when information is shared only among immediate neighbors. Furthermore, like the jellyfish, cycles will become even more common if the communication channels are directional.

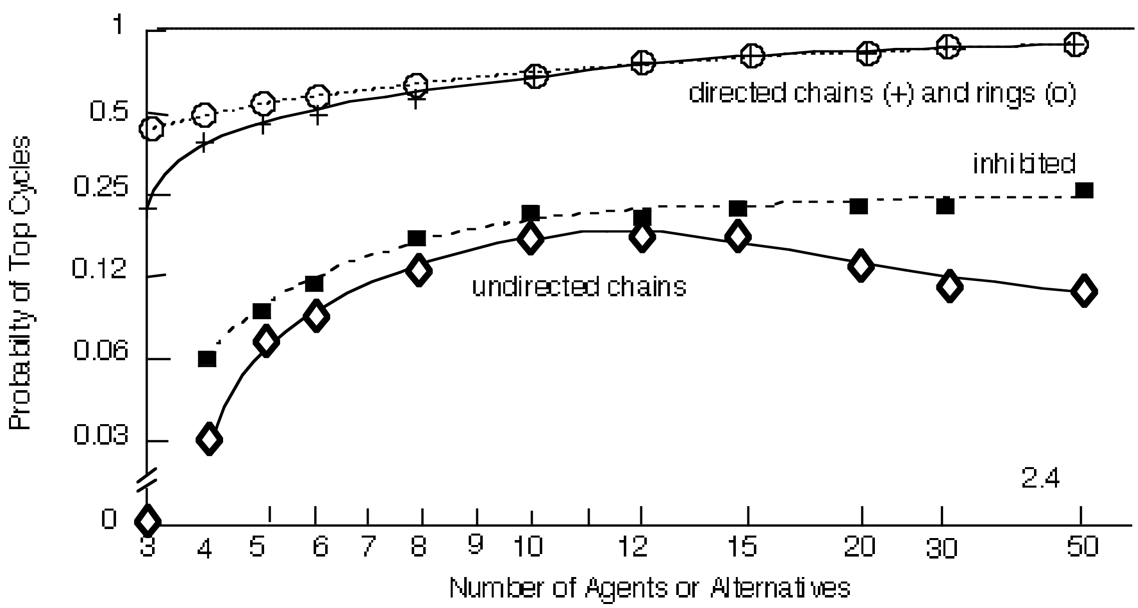

Fig. 2.4. Replacing bi-directional edges with directional edges raises the odds for top cycle by 6-fold or more (top curve, plusses and circles.) However, inhibiting weights on the nodes can push the top cycle probability back down towards that found for bidirectional chains (lower curves.)

Figure 2.4 illustrates. With undirected communications between neighboring agents, the top-cycle probability reaches a maximum of about 15% for a chain of 10 – 12 agents (diamonds.) If directionality is introduced into the social network (plusses), then cycle probability rises 5-fold to 60 – 70%, increasing further as the chain length increases, eventually reaching 1 as the asymptote. Directed ring anigrafs behave similarly (dashed line, open circles.) Anigraf social networks composed of chains thus have a high potential for eliciting periodic activities. Even rather small 8-chain anigraf worms with directional communications can initiate 5-cycle waves such as **AbdecA**.

2.4 Cooperative vs Competitive Networks

Anigrafs with directed, rather than with bi-directional communication channels come at a cost. Such networks marginalize one of our key assumptions about social awareness. Because information is passed only one way and not back and forth, the sharing of knowledge and preferences within the system is quite limited. Such networks resemble those with feedback loops. As a species, anigraf creatures with directed networks thus are second-class citizens and lie somewhere between a fully aware (bi-directional) anigraf and Braitenberg's more reflexive vehicles.

To clarify this connection, consider how we might shut down or control top-cycle activity, especially if it leads to chaos. Rather than removing directionality, a simpler solution is to shut down the voting weights of the agents (or, equivalently, assign equal weights.) This is easy to implement through either global inhibition or inhibitory feedback loops among agents. As the exchange of information among agents is reduced to zero, the probability of top cycles decreases and can be driven *below* the bi-directional result shown in Fig 2.4. (The inhibitory case plotted shows the attenuation effects, but not the limiting result.) The more agents whose clouts have been reduced to zero, the greater the chance of one agent getting its way. Our directed anigraf has then been morphed into a kind of hybrid between a Braitenberg vehicle and the truly social, bidirectional anigraf.

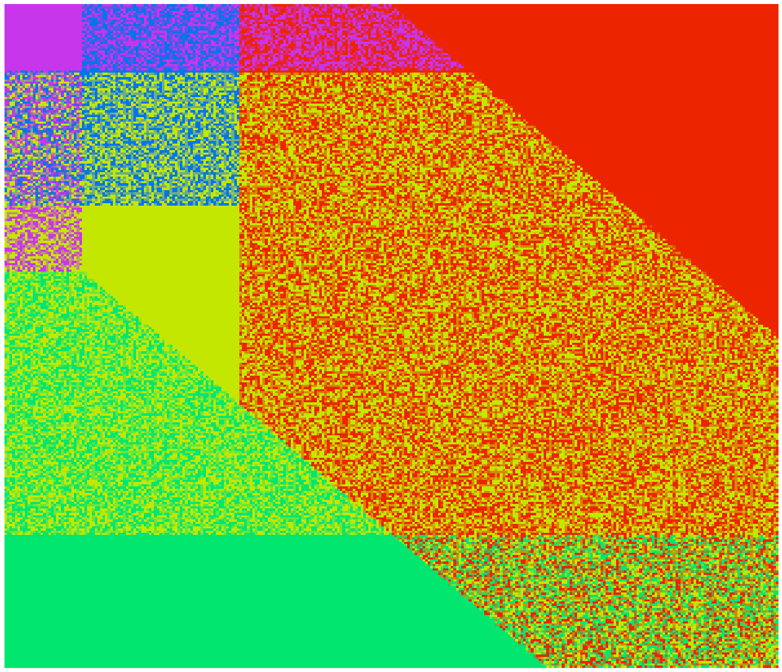

Plate 2: Phase Plot showing Winners for a directed 5-Chain Anigraf with weights (x = 0-10, 6, y = 0-10, 2, 6.) Textured areas are topcycles.

2.5 Brain Types

An obvious extension to swimmers (or crawlers) is to modify the neural network at the "head" end of the undulating chain. Already we have seen that simple head designs, such as pentagons or hexagons, terminate tail motion simply by setting the voting power of agent **A** to zero (Fig 2.2.) In Fig. 2.5 we illustrate further anigraf forms for "heads" attached to smart tails that consist of a chain of three or four agents. Consider the forked head. The notion is that activation of the left (**G**) or the right (**F**) member of the fork will tighten a muscle and cause the head to turn. Let this change in "head orientation" happen in the presence of the **Acd** cycle which is driving the anigraf forward.

Hence we need either an **Acd** cycle in the presence of a dominant **G** activation. Possibilities are **AGcd**, **AcGd**, or **AcdG**.

To set up the first of these cycles, the following Condorcet comparisons must result when the votes are tallied:

A > d; **G** > **A**; **c** > **G**; **d** > **c**; {**A, G**,**c**,**d**} > **b**, **F**.

To mimic a very simple voting system, let the strengths of the agent's desires take on one of three levels: noise, middle, saturated, or 1, 3, 6. (See appendix 3 for an elaboration using three continuous distribution functions with analogous mean values.) One voting regime that satisfies these conditions is {1,6,3,1,1,6} respectively for agents {**A**, **G**, **F**, **b**, **c**, **d**}. However, for this scheme to work,

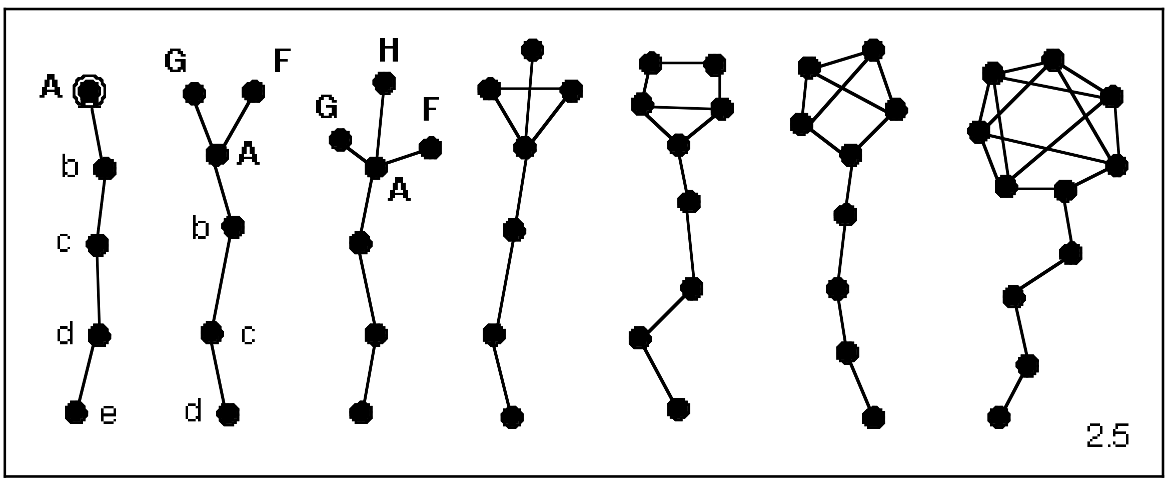

Fig. 2.5. A variety of swimmers or crawlers with different head designs for their smart (directed) tails. Plate 2 shows the richness of top cycles for a the simplest case on the left.

the preference orderings for each agent need to be restricted to two levels: first choice and second choice(s), with all other choices being equally indifferent (i.e. Kd =2.) In other words, the agents can only distinguish goals favored by their neighbors in the anigraf (and obviously the difference between these and their own goal.)

Even with alternatives limited by Kd=2, there are many varieties of behaviors possible for our little creatures with smart tails, and little brain-like "heads". A three-fork at the head of an appendage could activate not only turning to the left of right, but also perhaps local lunging by the middle agent **H** in the presence of the **Abd** swim. Such activation weights correspond to lunging forward to grasp a prey. More complex pentagonal networks that include "houses" might provide potential for agents with sensory apparatus that could trigger a host of body or tail movements once the adequate stimulus is sensed. Another obvious manipulation of the "head" is to add edges that join symmetric agents/nodes. In a Hexagon Anigraf (see front-piece), adding the edge BF will affect the preference orderings not only for B and F, but also C and E as well. Consequently, the cyclic probabilities change because agent's preference orders are altered. If the edge BE is added instead, bisecting the Hexagon, then we have a symmetry between ABC and FED, and we obtain still another behavior. Surprisingly, this latter addition will prohibit cycles, whereas the first increases the cyclic possibilities. Even with only six-node heads, there are over 100 possible anigraf designs. This number explodes to over 10,000 if 8-node graphs are considered. Hence there are many routes for Darwinian selection in a variety of contexts. Appendix 4 and Chapter 8 touch on some of these issues.

For very large rings, a potentially useful modification is to add edges that create local bridges, as in regular graphs, or distant bridges to create "small world rings." Each has quite different cyclic behavior. Another weird brain design might be to have two directional rings as illustrated in the front panel, with bridges between pairs of nodes on each ring. Or, two directional rings joined like Siamese twins. Turning rings on or off could cause opposite cycles, asymmetric body movements, etc. But even with such more complex "brains", these swimmers or crawlers execute only with wave-like movements of their chain-like tails. The specific "brain type" will have marginal influence on this coordination. Hence, when all is said and done, these anigraf swimmers have only a modicum of social consciousness among its network of agents.

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Anigraf3: Walkers
syncopated limbs

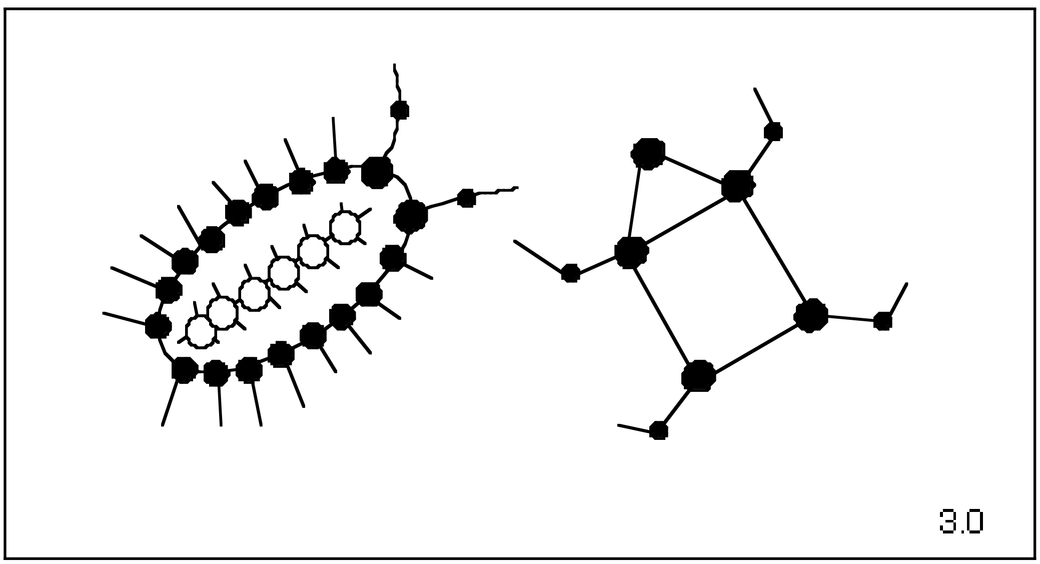

Fig. 3.0. Depiction of two types of legged anigrafs. As before, the nodes correspond to agents, with the small nodes located on limb segments. The open circles in the “centipede” control corresponding left-right pairs of “leg” agents.

28 Jul 07

3.0 Adding Limbs

Our most advanced swimmers locomote with wave-like motions of a segmented body. Resident within each segment was an individual agent. A chain of these agents guided a wave motion of the body or limb segments. To enhance the behavioral repertoire of such anigrafs, an obvious next step is to add more limbs. Alternatively, the chain of agents itself can be augmented, such as adding branches so the anigraf resembles a simple tree. Such additions place significant demands on the control structure of the anigraf "brain" required to coordinate the various agent activities. To illustrate these problems, we begin with creatures having many legs. As before, each leg has its own set of low-level agents that govern the type of movement of the limb. Movements of these separate appendages, or more specifically, the activity of these independent sets of low level agents, must then be coordinated to create a sequence of limb movements. The pattern of these sequences is a gait.

To solve the difficult problem of retaining body stability under gravity, we begin with six or more agent-controlled limbs, or legs. The most common gait is to lift successive pairs of limbs in a wave-like motion, thus insuring that most of the legs continue to support the body. This is a first step in an exploration of whether realistic gait patterns can be created in a single chain of body agents, or whether a control structure having two linked chains, such as a spinal cord, is more plausible.

3.1 Centipede Anigrafs

Imagine a creature with many limbs on each side of an elongated, cigar-shaped body (such as the sixteen-legged anigraf illustrated in the front panel). From head to tail, label these pairs of legs {al, ar},{bl, br},{cl, cr},...{nl, nr}. The notation indicates that the left and right legs in each pair are moved together. Hencewe can place the N controlling agents in a central chain, or "cord" (such as is implied by the open circles in Fig. 3.0.) Then a wave-like motion of the limbs requires an N cycle among the agents, ordered sequentially, as in a cascade. But already we know from Anigraf2 that if $N > 6$ or certainly 8, almost surely a directed chain of communications between neighboring agents will be needed. Furthermore, for large N, only a very restricted set of voting weights will create the desired wave. In effect, the anigraf construction has been reduced to a reflexive machine. Although a small group of agents located at the head of the cord could trigger a wave motion, to date we have found no social network can create a traveling wave that propagates down a cord with many segments. Social networks that control gait patterns appear to be limited to small numbers of agents. This implies that the creatures should have no more than about eight limbs, or, at most, six or eight states if pairs or triples of limbs are linked together.

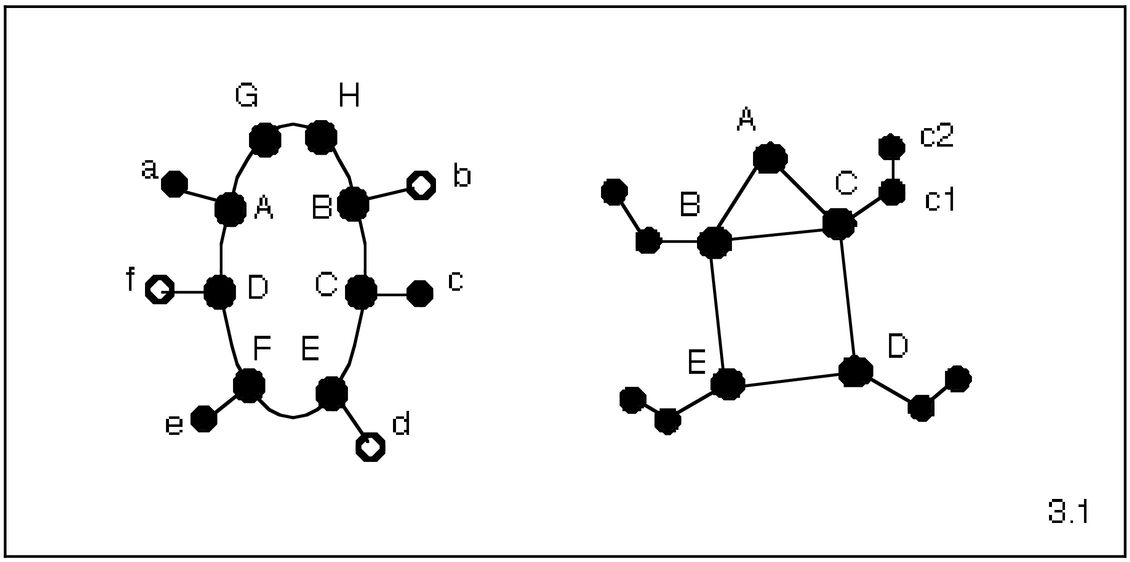

Fig. 3.1. Two different legged anigrafs: a cockroach and a quadruped.. Upper case indicates a gait control node; lower case, or small nodes are agents on limb segments. Two gaits for the cockroach are indicated (see text.)

3.2 Cockroach Anigraf

This six legged creature has two gaits: one is a wave, the other is called the “tripod”. The wave gait is the same as in the centipede, but with fewer legs: first the front two limbs are moved, then the middle two, and finally the last two. The tripod gait, on the other hand, simultaneously moves three limbs located at asymmetric positions, as illustrated in Fig 3.1 by the solid and open nodes. Both schemes preserve balance.

Like the centipede, either the cockroach wave-gait or the tripod gait could be produced by some simpler reflexive automaton, activated when a social network of “head” agents picked either agent “T” (tripod) or agent

"W" (wave) as the winner. On the other hand, unlike the centipede, the cockroach has only six legs. Now only four agents are needed along a central cord to create the wave gait, because we only need at most a three cycle that activates one of three pairs of legs (or a pause if the tripod gait is selected.) Furthermore, many different top-cycles can be created. This opens the door to a socially-based anigraf network for innervating limb motions. We can move still further away from automata-like systems by positioning one more agents on each of the six limbs, as shown by the lower case nodes in Fig. 3.1. These "second-tier" agents, a - f, can serve two functions: (1) they can provide a basis for invoking local cycles such as B, C, c, D, B, as well as (2) having the potential to bend a two-segment limb.

3.2.1 Limb Configurations

Although we could proceed as before, and determine the voting strengths needed to generate sequential limb motions, it is more productive to consider first each limb in isolation, driven by its own local cycle. With neighbor-only communications (Kd = 2), the minimum number of agents needed to create cycles is five if the agents are networked by a ring or a tree, and four if they are networked by a chain. Obviously at least one of the agents must be part of the body, because this will be the agent that is activated by consensus with the other body agents.

Fig 3.2 illustrates some of the minimal arrangements for agents that could govern limb control. Cycles for the simple chain and ring have already been elaborated in Chapt. 2. In each case we have incorporated the top agent (large circle) as a member of the anigraf's social repertoire. However, such agents must also be linked to others having the same social status. Hence a possible variant is to have two agents, rather than one, as part of the body structure (middle illustration.) But if two agents are on the body, then the limb

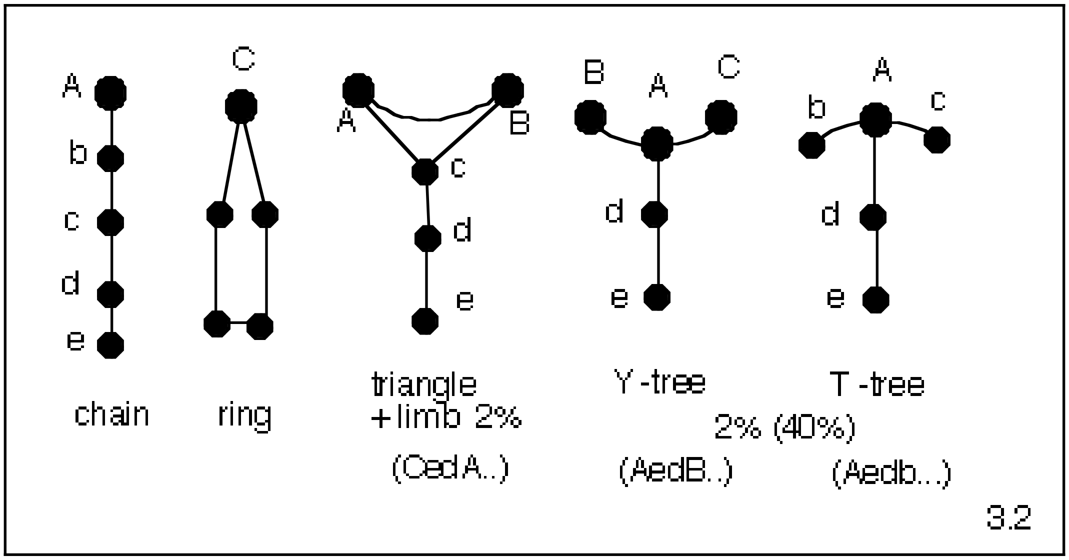

Fig. 3.2. Designs for local control over limb agents.

must have at least two segments. This follows because a one-segment limb would have a total of only 4 agents, with one connected (or covering) the remaining three. Hence we need a minimum of five agents, which is satisfied with a two-segment limb.

Placing two agents on the body creates a possibly awkward triangle arrangement at the head of the limb. A more agreeable configuration is to have three agents at the top, with two other agents on the limb, thereby forming a "Y" or a "T" - tree as shown in the last two illustrations. Now all three of the top agents can belong to the body set of agents, or, alternatively, only one of these agents is part of the body set and the remaining two are lower-level, being part of the limb activation system, which here we represent as an upward arrow configuration (far right in Fig. 3.2). Unfortunately, in all cases, the probability for achieving cycles using random voting is only 1 - 2 % for undirected graphs. However, with a three-level restriction on five weight choices (e.g. mid,hi,lo,lo,hi), the range of levels used earlier for directed chains in Chapt. 2 will yield a 40% or higher probability of certain 4-cycles. (See Plate 2 for a slice through this 5-dimensional phase space.) Now, with weights "d" and "e" restricted appropriately, either an AedB or and AedC cycle can be activated simply by raising agent A's clout from zero to the upper third of the range of weights.

3.2.2 Spinal Cord Configurations

In animate forms, limb movements are sequenced in part by activity that moves down a spinal chord. A set of stacked "Y-trees" or "T" – trees resembles this spinal configuration. In Fig 3.3 a three-level chord is illustrated at the far left. This chord has four sets of limb segment agents (open circles, attached at positions A, B, D, E.) The bilateral symmetry of the chord is forced by the need to place limb segments on opposite sides of the anigraf. Activating local cycles in each limb segment is now trivial: First we freeze weights for the limb agents, choosing suitable values for cycles. Then we need only activate A, B, D, or E in the chord. A more abstract version of this chain can be obtained by unfolding the chord, and is illustrated to the right.

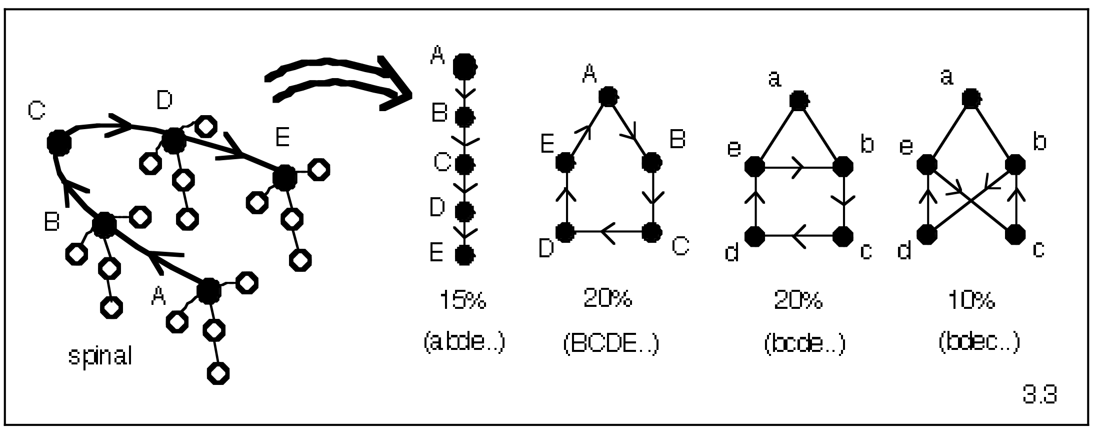

Fig 3.3. Spinal chord construction (left.) Possible modifications of local structures within the chord are shown at the right, with the probability of top cycles indicated if weights chosen from a uniform distribution.

Other, probably less attractive modifications to the spinal chord configurations would include closing the spinal chain to form a ring, or joining bilateral components of the chord to create a "house" graph. We can also influence the type of cycle desired by changing the graph structure. To generate "figure 8" cycles, nodes should be connected in a criss-cross manner as illustrated at the far right of Fig. 3.3. In each case, the cycle can be turned on or off by appropriate settings of the weight or clout of a body agent. Clearly, directed channels play a key role in setting up the desired cycle. To re-iterate, with undirected channels, the odds for a 4-cycle are typically only 1 or 2 percent; with directed channels, about 10 to 20% of random weight selections will be successful, with still further improvements using three-levels of voting strengths. The combination of both methods can insure that over 80% of the voting weights will yield an abde cycle for the simple chain. Thus, three factors govern how easily 4-cycles can be generated using social networks: (i) the configuration of the graph, (ii) the choice of which edges (channels) are directed, and (iii) whether voting strength is chosen from uniform distributions, or from one of three ranges (e.g. lo, mid, hi.)

3.3 Quadraped Gaits

Generating cyclic movements for four (or two) limbed anigrafs appears plausible using one of several variations of spinal chord networks described. A remaining issue is to control the sequence dynamically to maintain balance, as the transfer of power moves through the chord. Surprisingly, Raibert(1988) has shown that a rather simple machinery suffices if the limb (and body) motions satisfy certain “sinusoidal” constraints. The problem is then the coordination of the cyclic activities: we must have a sequence that runs off a clock and interleaves the limb movements properly.

To engage in a walk, a minimum of a four-cycle among agents is required, even if we have a biped anigraf. (There can be no two-cycles.) For our minimal quadraped to maintain balance, the right front (Rf) and left rear (Lr) limbs should move together, and similarly for the two remaining limbs (Lf, Rr.) Hence only two sets of limbs need be controlled, together with two appropriate pauses between movements. Alternatively, we eliminate the pauses altogether and use each agent to activate limbs in sequence. This would generate a Lf, Rf, Rr, Lr sequence, for example.

Table 3.1 lists other gaits possible with the simple 4-cycles. How can this set of gaits be generated using one social network? Ideally, we would like to envision the top-cycle sequence of agent activities as having a simple mapping to the desired movements. To accomplish this, the anigraf map of the similarity relationships between agents need to have both left-right and rostral-caudal symmetry, because this is a property of the gait sequence. The pentagon or

Table 3.1

Gait Type		**Sequence**		
walk	Lf & Rl	pause	Rf & Rr	pause
jump	Lf & Rf	pause	Lr & Rr	pause
cantor	Lf & Lr	pause	Rf & Rr	pause
run	Lf	Rr	Rf	Lr
bound	Lf	Rf	Lr	Rr
gallop	Lf	Rf	Rr	Lr

"house" with directed communication channels are the simplest anigrafs that satisfy this condition. As shown in at the right of Fig 3.3, paths through these directed graphs correlate nicely with the resultant sequence of the legs. Hence, unlike most linear networks with resonant modes (Greene, 1962), we have a pleasant mapping between how agents view their relationships to one another -- a cognitive stance -- and the cycles among the limbs effected by the agents -- a physical consequence.

Note that the above proposal also requires a two-tier system: a set of (five) body agents, or mental controllers, that specify the sequence of limb movements, and another sub-set of three or four "robo-agents" that activate the bending movements of each individual limb. These local agents should be seen as part of the lower tier "Y" or "T" network, with at least one of the body agents lying at the junction of the network. This latter agent is in a key position: its vote can simultaneously either activate or shut down both the cycle among the body agents as well as the local cycle among the "robo-agents in the limb. Hence both the activation of the limb as well as its own bending movements are coordinated in the sense that there is one "body" agent in common.

3.4 Gait Switching

One of the great benefits of a social computation is that behavior can be changed dramatically, yet predictably, by one vote. For example, we may wish to change the quadraped's gait from a "walk" to a "gallop", or perhaps simply change a walk from forward to backward. One obvious scheme for gait switching is to change directed channels in the graph, such as from a "house" to a "criss-cross" construction (See Fig 3.3.) However, more preferable would be to leave the network unaltered, and simply change the voting power of one or more agents. The use of three-level weight selections makes gait switching even easier.

A precursor to simple, but sophisticated gait switching is already present in the limb segment. The top of a Y or T network has three agents, at least one of which is a body agent. Cycles involve either the right or left arms of the Y or T, but not both. If the Y configuration is used with three body agents, then each of the two cycles could make slightly different adjustments of the limb position, as would be necessary for either forward of backward movement. Similarly, if a T configuration is used to control limb motion, then the two different local cycles might effect a small lateral adjustment of a limb motion, as would be needed for turning either left or right.

More complex gait changes involve going from a walk to a run, or to a gallop. Referring to Table 3.1, a "run" maps into a 4-cycle around the lower square portion of a house (see Fig 3.3), whereas the "gallop" requires a criss-cross sequence shown in the adjacent graph. To obtain both 4-cycles using the same network, and for a significant portion of the weight space, it is convenient to add a sixth agent. One suitable configuration is a hexagon with two directed diameters, as illustrated in Fig 3.4. Another is a directed k-partite graph (right.) For the modified hexagon, two relevant 4-cycles are bcde... (gallop) and bcde...(run). Only about 3 percent of the weight space will support these 4-cycles. However, once again, the use of three range levels of weights will yield cycles 30% of the time, or more if the range of each level is narrowed. One suitable set of weights for becd and bcde cycles are (lo,**mid,hi**, hi, mid,lo)

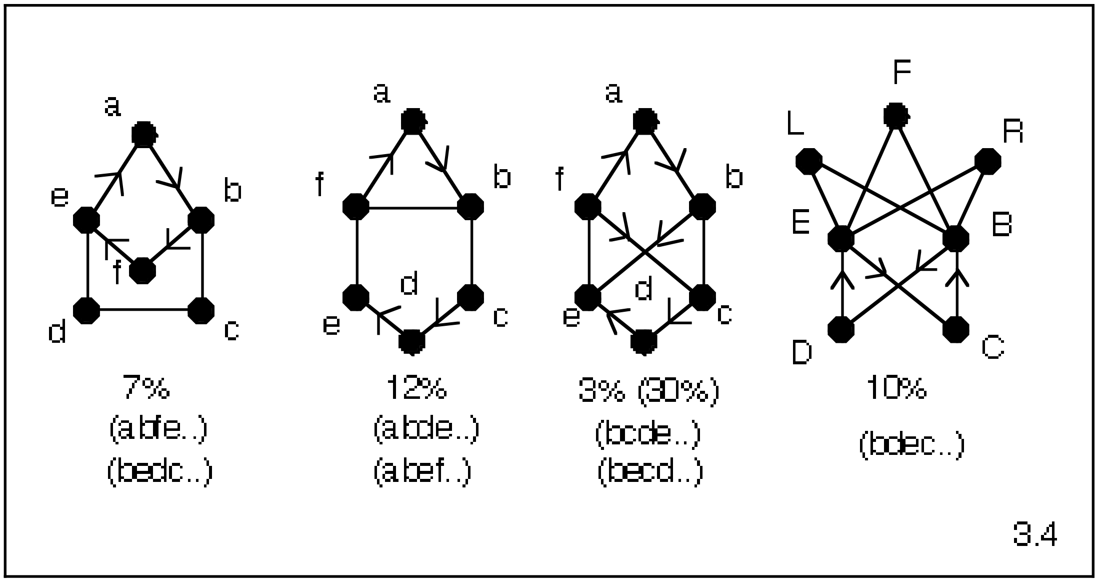

Fig. 3.4. Anigraf patterns that can elicit 4-cycles, Percentages are for weights taken from a uniform distribution, excepting the 30% in parentheses, which uses only the three levels. The second pattern is used in Plate 3.

and (lo,**hi,mid**,hi,mid,lo.) Note that the difference is simply a switch in the voting strengths for the second and third agents.

Other configurations of interest include the pentagon with a sixth node added to the interior. With channels directed as illustrated in Fig 3.4, we can obtain either an abfe or a bedc cycle. The latter corresponds to the customary 4-legged quadraped walk. The abfe cycle, however, engages only two of the four limbs. Various roles can be assigned to agents A and B. One intriguing possibility is if they controlled both body stance and balance as well as a “pause”. Then the abfe cycle would allow an “erect” anigraf to engage in a walk, while the bedc cycle for the same anigraf would control a four-legged run. In each case, suitable weights for these cycles are potentially accessible using a three-levels of voting strengths.

Approximately 18 different gaits have been observed in quadrapeds (Hillebrand, 1966.) With five agents, we have about 300 possible acyclic connected digraphs; with six agents, about 6,000 possibilities, and with eight agents, over 20 million. So there are many configurations available to generate 18 different gaits. But it is quite difficult for any given configuration to generate more than a few 4-cycles, over a significant range of weights. If 6 or 8 cycles are required, then plausible solutions almost vanish. One would have to overlay several different graph structures and then activate each independently, or allow "on-line" modifications of the structure of the digraph. These properties are quite unlike linear resonant networks that have many [O(n^2)] solutions for any one 4-cycle. Curiously, in real animate creatures, the most gaits seen is about six.

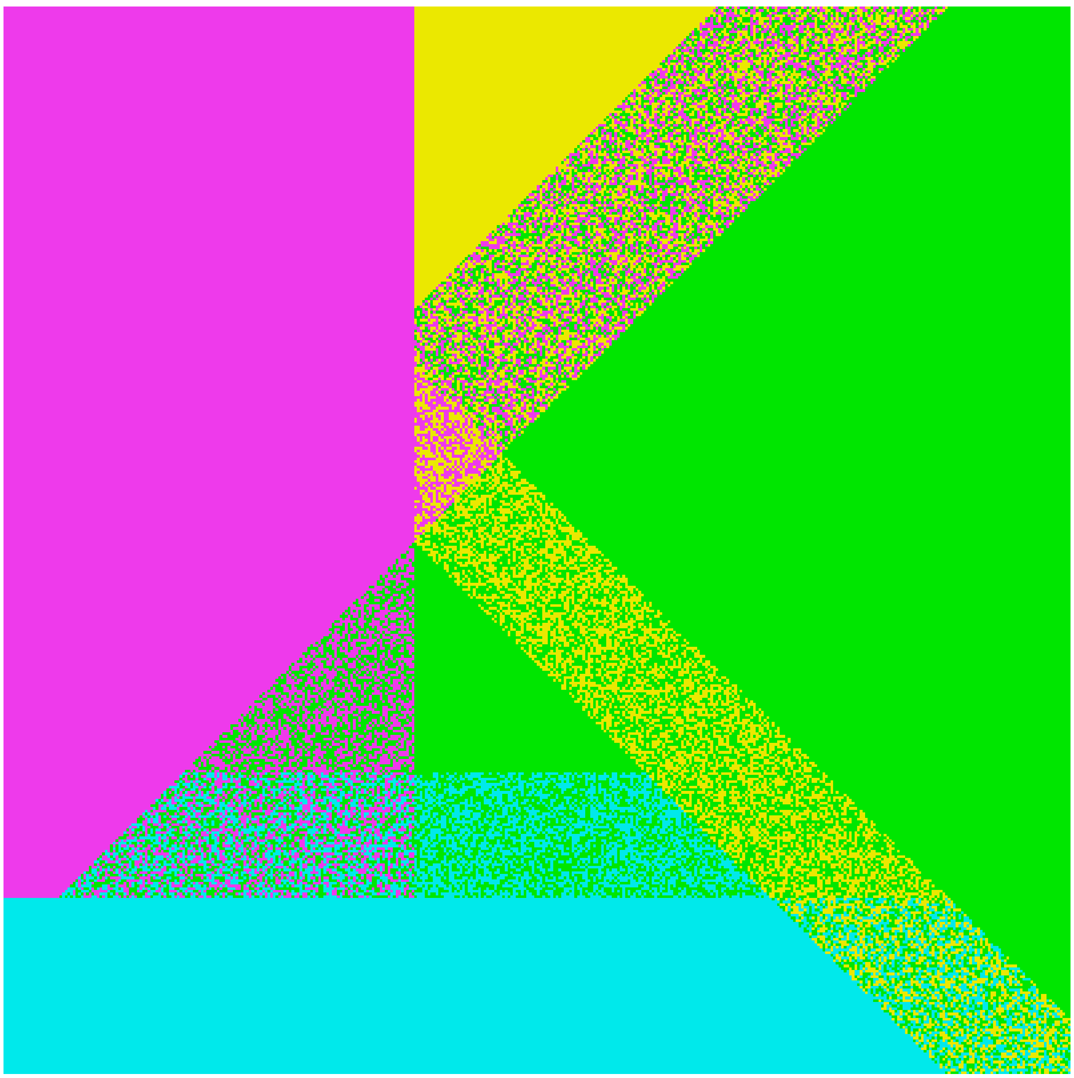

Plate 3. Phase plot for second anigraf from left in Fig. 3.4 showing a range of 4-cycles as a textured streak rising to right from middle of panel. Weights are (1, 3, x = 0 – 6, y = 0 – 6, 3, 1).

3.5 From Gaits to Goals

For very simple Anigrafs -- those we regard as akin to the minds of insects or other reflexive creatures, we have a situation not unlike our five daemons trying to control a vehicle. Specific goals such as “flee”, “approach”, or “avoid” are closely associated with particular locomotive movements such as “run”, “walk”, or “turn”. In these cases where there is a simple one-to-one relation between the gait and goal, we can assign specific goal states to each gait agent. To illustrate, let the set of goals be “flee”, “attack”, “approach”, “avoid”, “reflect/watch”, “retreat”, each be associated with the movements of run-away (R-), sprint forward (S), walk (W), turn (Tr, Tl), halt (H), backup (B). How the creature behaves in a given context will then depend on how these movements and their associated goals are related.

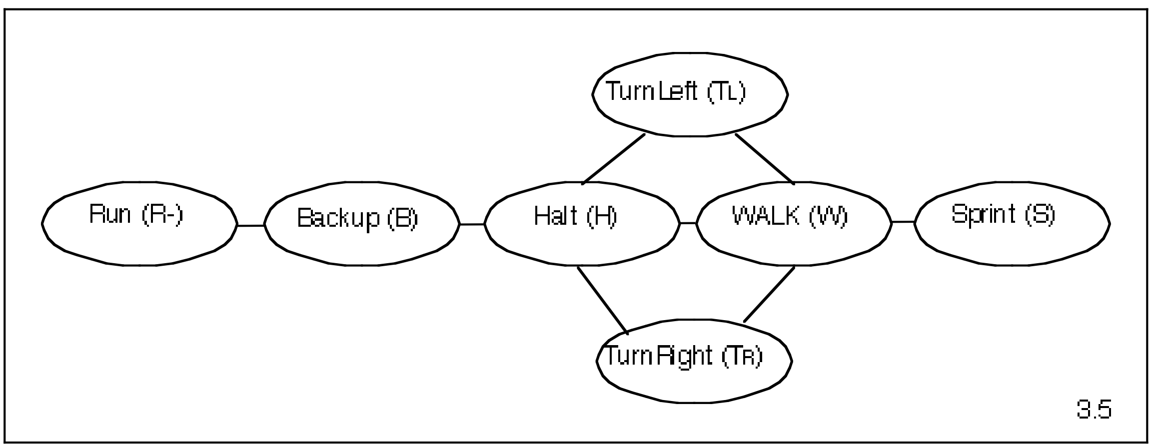

Fig. 3.5. High level anigraf that relates different types of movements, reminiscent of the puppet’s options considered in the Preliminaries.

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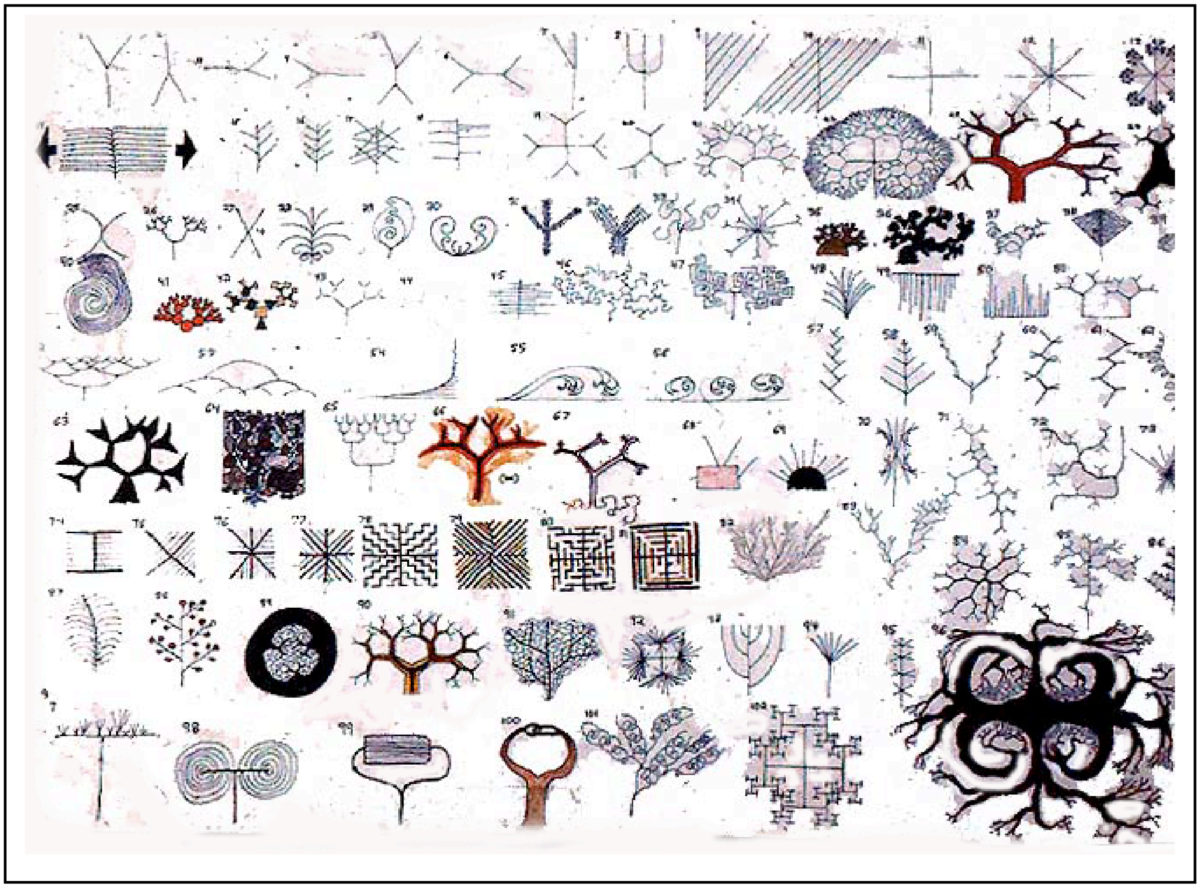
One possible relationship for these behavioral acts is the anigraf show in Fig. 3.5. Fast attack (sprint forward) is seen related to an approach (walk forward), backing up is a form of retreat, with fleeing the extreme version. Turns are usually executed at low speeds while walking, or when stationary. Although cast in terms of movements, the controlling agents now are engaged in another level of social consciousness, one having a clear emotional content. Flee implies fear, approach implies curiosity; attacking is an aggression. These agents have a character one might associate with the daemon-like mental organisms. Cognitive capabilities are emerging.



'Tree-like" Forms (from P. Gunkel, the *Ideonomy Project*.)