A simplistic view of mind would be to regard a collection of vehicle-like organisms as a complex, multi-input controller. Each organism would be designed to control one variable, such as food cravings, sexual activity, foraging, and for members of bartering societies, costs, benefits, and liabilities. The encapsulated set of such organisms would then evaluate trade-offs over many control variables. This is the common view of how brains are organized. However, how should the craving for food be compared with sexual activity, or the need to discuss a problem with a colleague? How should degrees of risk be mapped into a pleasurable experience? Without some measure common to all choice dimensions, the typical homeostatic feedback controller becomes inadequate. This leads us to consider the collection of encapsulated organisms as social-decision makers, guiding complex behaviors by reaching a collective choice. The preliminaries that follow argue for a special procedure for aggregating opinions, desires and needs of a group of such mental organisms that occupy the same physical entity. Regardless of the complexity of the animate biological system, the same procedure for reaching a group consensus is used, simply because this method can be shown optimal. Successful biological systems achieve optimality when possible, and we expect the constituent mental organisms to do no less.
1.0 Pandemonium: babble

Imagine a complex vehicle occupied by five semi-autonomous modules, which we will call daemons. Each daemon has a different goal, in this case, attack, flee, hide, etc. (Fig. 0.1). As shown by Braitenberg, rather simple neural machinery can underlie the behavior we attribute to each of these simple daemons. These individual behaviors, such as attack or flee, are seen as the mental correlates of the underlying hardware, put into place by the architect’s intent. The design of these individual behaviors will have structure in its own right, characterized separately from the physical embodiment. Collectively, there will also be yet another, more cognitive social structure that reflects how daemons interact with one another, and how they reach decisions as to what their complex vehicle should do next. Given that daemons have different and often, competing goals, how can they reach an agreement for the next collective action, also insuring that this choice is rational? For our toy example, what maneuver should this vehicle make?
1.1 Social contracts

Obviously, the strength of a daemon’s desire will vary depending on its observations, needs and context. A very simple scheme for choosing the next maneuver would be to give control to that daemon with the strongest desire. If this were a shouting contest, then the voice heard over all the babble will win out, and, as illustrated in Fig 0.2 right, the vehicle’s action will be to Attack (A). This is the Pandemonium algorithm advocated many years ago by Oliver Selfridge, and is still one of the most favored methods of choosing winners.

However, another scheme, more typical of physical systems, would be to assign force vectors to each possible action, with the length of the vectors corresponding to each daemon’s desire. In this case, when vectors are added, the resultant most often will point between categories, as illustrated in Fig 0.2 (left). But half-hearted choices which that meld two or more categories are inconsistent with most animal behaviors. Regardless of the complexity of all the mental acts they might entertain, our daemons will make categorical choices. If group choice is to be made by some vector addition scheme, the vector closest to the resultant will become the sole winner. For our toy example, then, the group’s choice would be to Flee (F), rather than to Attack(A) as the loudest daemon would prefer.
Fundamental Hypothesis I

Daemons, or more generally agents, will choose one category for action, but never a mixture of two or more categories.

This behavior is rooted in how the external world is viewed. Observed events, objects, actions, etc. most often fall into categories. Examples include the hierarchical structure of animals, plants and their variations; the formation of communities into villages and cities; social customs and laws; our arrangement of the elements into a periodic table; and, of course, how we classify types of emotions, as well as their associated actions (Darwin.) Classification by categorization is one of the simplest ways to view a world, especially where a convergence of multiple constraints are typically imposed upon form and function (D’Arcy Thompson, Richards & Bobick, Marr.)

Fundamental Hypothesis II

Daemons, or agents, that occupy the same vehicle all see the set of possible actions having the same relationships.

This constraint applies to an ideal cognitive world, where all agents have identical models for how objects, actions, events, etc. are related in a given context. For example, we regard the shape of and color apples more similar to that of tomatoes than to bananas, the sounds of string instruments more similar to each other than to percussive sounds, or play more similar to fighting than to sleeping. These relationships can be measured using Multi-Dimensional Scaling (Shepard,1980), or Trajectory Mapping (Richards & Koenderink (1998), the difference being that the latter method generates a graph. Figure 0.2 illustrates.
We may wish to further amend either of the above two methods to insure that only very robust decisions are made. For example, if the plurality shout was less than one-half or two thirds of the total volume of shouting, then no winner would be chosen, and the vehicle would simply continue with its current action. Alternately, if the resultant of the vector is either too small, or lies within an angle of the bisector of two action vectors, again no decision would be made. Adding these conditions avoids cases where the loudest shout is very near the noise level, or when the vector resultant is ambiguous.

Even with these few simple examples, already it is obvious that the method for aggregating opinions and desires can have a critical impact on which action will be taken. Regardless of the complexity of Braitenberg’s vehicles, a social contract for choosing winners must be held by the vehicle’s occupants. If the strengths of desires are seen as votes for different alternatives, then a procedure must be in place that dictates how “votes” should be counted. Is there one tally procedure that is optimal?

2.0 Intrinsic Knowledge

Returning again to Fig 0.2, we note that the various actions are not independent. Flee is the opposite of Attack, and hence these actions would be negatively correlated in any rational world. Similarly, Inspecting a novel event will require approaching an object, and may be a precursor to an Attack. Hiding has some features in common with standing completely still (Freeze.) Such correlation represents intrinsic knowledge about the how behaviors are seen to be related. They can be used to place choices for action in a metric space (Shepard, 1970), and provide an important constraint for achieving an optimal aggregation of choices, regardless of the complexity of the social system.
To see the impact of shared intrinsic knowledge on group decision-making, let the space of possible actions be related as shown in Fig. 0.3. These relationships are exhibited in two ways, one metric, the other, non-metric. Note that in this particular case, the non-metric graph has been formed by making explicit the steps between regions highlighted in the left panel. We will return later to the effects of resolution within the metric space on collective outcomes. For now, the focus will be on non-metric, graphical representations for the similarity relations between choices for actions.

### 3.0 Social Connections: Bartering

All social contracts described earlier for picking winners assume that the daemons’s choices are independent. Thus, there is no need for one daemon to communicate her desires to another. But if some choices are similar or related to others, then this information has value in choosing winners that come closest to maximizing the preferences of the group. For example, what if a daemon’s desire could be at least partially satisfied with an alternative choice that is close to, but slightly different than her first choice? Certainly obtaining this second option would be better than not winning anything at all.
3.1 Preference Orders

Returning to our five vehicle occupants, consider again the choices. As implied in the right panel of Fig 0.3, linked nodes in the graph share common features. Attack (A) and Inspect (I) are forward movements of the vehicle, the first being more aggressive than the second. Fleeing and Hiding are backward movements, and share the feature of “fear”. Freeze, on the other hand, suggests uncertainly between aggression or fear. Given these relations, we would expect Daemon (F) whose first choice is fleeing, would lend support either Hide or Freeze over the actions Inspect or Attack that take the vehicle closer to a perceived threat. The reverse, however will be true for Daemon (A) who favors an attack and who will most likely regard Inspect (I) as the best back-up maneuver. The similarity plots of Fig 0.3 thus makes explicit the rank ordering of the alternate choices for any Daemon.

We now can engage in a modification of our original social contract, where daemons can have the hope of at least getting a second choice preference if their first choice is not likely. Let us add to a daemon’s shout the voices of all its neighbors on the similarity graph (e.g. Fig 0.3.) These neighbors correspond to a daemon’s second choice. We now have included more information about preferences in the decision-making process. For our example, Daemon A’s level of shouting will be augmented from 7 to 7+8=15. Similarly, Daemon Z’s new shout increases his voting strength from 0 to 0+8+10+4 = 22. The row labeled “Top Two” in Table 0.1 shows that this procedure picks Freeze (Z) as the winner. Note that this winner, unlike those before, is the first or second choice of all but one of the Daemons.

A further improvement on the social aggregation method was suggested many years ago by Borda (1787.) The advance was to place less weight on second choice, still less on the third, and so forth. If we restrict ourselves to considering only first and second choices, we then would give a weight of “1” to a first choice, and “1/2” to a second choice, as shown by the rank vector in the second column of the last row in Table 0.1. The Borda winner is Flee (F).
(footnote: the proper Borda method is to multiply node weights by their ranks, picking the minimum sum as the winner. The abbreviated reverse Borda used here is more convenient for illustrating Anigraf properties.)

Table 0.1 First Tally Results

<table>
<thead>
<tr>
<th>Contract</th>
<th>RankWgts</th>
<th>F(10)</th>
<th>H(4)</th>
<th>Z(0)</th>
<th>I(8)</th>
<th>A(7)</th>
<th>Winner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vectors</td>
<td>[ ]</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>Plurality</td>
<td>[1, 0, 0]</td>
<td>10</td>
<td>4</td>
<td>0</td>
<td>8</td>
<td>7</td>
<td>F</td>
</tr>
<tr>
<td>Top Two</td>
<td>[1, 1, 0]</td>
<td>14</td>
<td>14</td>
<td>22</td>
<td>15</td>
<td>15</td>
<td>Z</td>
</tr>
<tr>
<td>Borda~</td>
<td>[1, .5, 0]</td>
<td>12</td>
<td>9</td>
<td>11</td>
<td>11.5</td>
<td>11</td>
<td>F</td>
</tr>
</tbody>
</table>

By now it should be obvious that the procedure used to aggregate the desires of our daemons can have a huge impact on outcomes (Arrow, 1960; Saari, 1998.) Even if information about the choice domain is incorporated into choosing winners, our daemons may still argue over just how second, third, etc. choices should be weighted when votes are tallied. All will agree that second choices should be included in the count, for then there is a clear individual benefit for the majority. But how to settle the rank weighting of second choices?

3.2 Condorcet Contract

In 1785 Marquis de Condorcet proposed a scheme that avoided placing weights on lower ranked preferences. His trick was to compare two alternatives at a time – like a tournament – to determine which one is preferred over the other. Now no weighting vectors on ranks need be imposed; each daemon will simply vote for the alternative in the pair that is more desirable, i.e. whichever member of the pair is higher ranked in his preference ordering. If one alternative is then found to beat all others in such a pair-wise contest, that alternative is seen as “the fair” social choice for the winner. More importantly, this Condorcet winner can be shown to be the maximum likelihood social choice (Young, 1998. Richards, 2002.)
Table 0.2 sets up a portion of this tournament. The first row gives the voting strengths of the five daemons. The next four rows illustrate how each pair-wise vote is taken. For example, in the first of these rows, F is pitted against I. How will Daemon(F) vote? Obviously he will choose F over I. Hence alternative F will receive a vote of +10 from Daemon(F), as shown in the second column of the second row. Next, when Daemon(H) votes between F and I, because alternative F is nearer in the similarity graph (Fig 0.3), Daemon(H) will cast its vote for F, adding another +4. Daemon (Z)’s position, however, lies equidistant from both F and I, and hence he is indifferent between the two choices, not contributing a vote to either. Daemon (I), of course, votes -8 for itself, the negative sign indicating that the vote is cast for the second member of the pair being considered. Finally, for

<table>
<thead>
<tr>
<th>Pairs</th>
<th>F(10)</th>
<th>H(4)</th>
<th>Z(0)</th>
<th>I(8)</th>
<th>A(7)</th>
<th>Total</th>
<th>Winner</th>
</tr>
</thead>
<tbody>
<tr>
<td>FvsI</td>
<td>10</td>
<td>4</td>
<td>*</td>
<td>-8</td>
<td>-7</td>
<td>-1</td>
<td>I&gt;F</td>
</tr>
<tr>
<td>HvsI</td>
<td>10</td>
<td>4</td>
<td>*</td>
<td>-8</td>
<td>-7</td>
<td>-1</td>
<td>I&gt;H</td>
</tr>
<tr>
<td>ZvsI</td>
<td>10</td>
<td>4</td>
<td>0</td>
<td>-8</td>
<td>-7</td>
<td>-1</td>
<td>I&gt;Z</td>
</tr>
<tr>
<td>IvsA</td>
<td>10</td>
<td>4</td>
<td>0</td>
<td>8</td>
<td>-7</td>
<td>+15</td>
<td>I&gt;A</td>
</tr>
</tbody>
</table>

* = “indifferent” between the two choices

Daemon (A) choice I is closer to his main desire than choice F, hence its vote is cast for I, as shown by the –7 entry. The sum of these entries is –1, indicating that I is the pair-wise winner over F. Following this procedure, the winner for the Condorcet contract is shown to be Inspect, I, which beats all other choices.

The Condorcet pair-wise winner thus has three advantages: first, there is no need for a rank vector when aggregating lower ranked preferences; second, this winner can not be beaten by any counter-proposal, as long as the similarity relationships among the alternatives and weights remain the same; and third, as mentioned, this procedure gives the maximum likelihood choice. Biological systems enforce optimal choices. Thus, although perhaps superficially complex, our social tallies that follow will use this method for
aggregating votes, regardless of the complexity of the system. A simple Condorcet tally machine is described in Appendix 3.

4.0 Anigraf Abstraction

The mental organisms we have called daemons form a social structure, which is represented by a graph showing the similarity relations between the desires of each daemon. This graphical depiction is called an Anigraf. Figure 0.3 is one illustration, Figure 0.4 another. Note that each vertex of the Anigraf corresponds to a mental organism, or daemon, with a unique set of preferences. The edges of the graph show which daemons share similar preferences. The Anigraf not only makes explicit the similarity relationships among these daemons, but also shows viable communication channels between them. This property follows from the simple fact that meaningful communication of preferences is not possible unless the two parties share in part the same belief structures. The Anigraf is thus a social network, but one in the internal cognitive world of mental organisms.

In a fully connected graph, all daemons will share their desires for the social system with each another. In a ring or chain, preferences are shared only with at most two other agents. In more complex Anigrafs, the connectivity will be extensive, with preferences of many daemons similar to one another. The variety of graphical forms we will study range from simple rings of five nodes to very complex scale-free graphs with hundreds of nodes, each representing a different mental organism with different desires.

Just like each daemon could control some aspect of a vehicle, so will our daemons be capable of initiating actions, provided the aggregate system makes a collective decision to do so. In the early stages of Anigraf evolution, we allow certain daemons to initiate a "leg-like" movements or "waves of an appendage. For example, in the chain network, if the aggregate approves the wishes of one of the daemons situated at the end of the Anigraf chain, then this daemon might command a travelling wave that propagates through the actual physical embodiment. Such potentials for actions lead us to behaviors like walking or swimming. It is important, however, not to confuse the Anigraf, which is a
mental construct, with the physical acts that the mental agents initiate. The duality between mental acts and physical actions is best thought of as a set of puppeteers each of whom control specific physical components of the entity they occupy. If you will, the daemons pull the strings of the puppet in which they reside, thereby translating mental acts into physical actions. Thus, there is a close coupling between decision-making and mechanisms for action. However, the thrust of Anigrafs is not the physical structure, but rather the cognitive designs, and how these designs constrain thought, decision and action.
and consequently behavior. More broadly, we wish to understand how behaviors are selected by the mental organisms that occupy creatures from simple cells to complex mammals.

To summarize, an Anigraf is a social network of mental organisms, which we will henceforth call “agents”, with the following properties:

1. The Anigraf is typically depicted as an undirected graph.
2. Each node, or vertex, in the graph corresponds to an agent (daemon) with a unique first choice preference for the next state of the social system.
3. Each edge in the graph indicates that there is a common feature or similarity relation between the preferences held by two agents.
4. An agent’s ranking of preferences is consistent with the Anigraf structure – i.e. the form of the graph.
5. Each agent has a say in the next state of the social system, with the strength of his vote a variable. This strength is a weight associated with the particular node that corresponds to the agent. Voting power increases (or decreases) with desire, or can be accrued by one agent representing a group of agents with identical preference rankings.
6. Aggregation of agent's desires will be done using the pair-wise, Condorcet procedure.

As we shall see, the particular social structure represented by the Anigraf plays a major role in determining whether the collection of agents will make common-sense choices that most would consider rational. Indeed, rational topologies for Anigrafs will be the major theme of the monograph. Arbitrary connections among a large number of agents who “go their own way” will be shown to create chaotic behaviors, whereas certain other topologies are guaranteed to yield comfortable aggregate solutions. The key is that the preference relations and belief structures of the constituent mental organisms, or agents, must be consistent with the knowledge about the world embodied in the Anigraf design. Hence there is a strong coupling between intrinsic knowledge and behavior. The sharing of the same global model among agents is an important component of Anigrafs, and leads to a social Gestalt, which is critical to achieving a collective consciousness.