How Is an Agent Like a Wolf?: Dominance and Submission in Multi-Agent Systems

Bill Tomlinson, Bruce Blumberg, Bradley Rhodes
Synthetic Characters Group / The Media Lab, MIT
20 Ames Street / Cambridge, MA 02139 USA
+1-617-253-5109
(badger | bruce | rhodes@media.mit.edu)

O Abstract

Agents are automating many tasks that used to be done by people. As agents begin to address more complex domains of human life, they will need to develop an understanding of the dominance hierarchies that people understand intuitively. We present examples of species with social hierarchies that occur in the natural world, in particular the gray wolf (*Canis lupus*) and the chimpanzee (*Pan troglodytes*), to show how an awareness of social status could benefit multi-agent systems. We present three main areas where dominance hierarchies could benefit these systems – as a mechanism for streamlining negotiation, as a means of facilitating mutually beneficial alliances among agents, and as a way of making interfaces to agents more intuitive for the people who create and interact with them. With regard to implementation, we propose that the three main elements necessary for an agent to participate in a social hierarchy are: an internal representation of its relationships with other agents, a means of communicating socially with those other individuals, and a desire to achieve its goals. As both a way of implementing multi-agent systems and as a means of understanding them, dominance hierarchies will be a valuable tool for creating systems that can mirror human complexity and thrive in complex social environments.

I Introduction

Social structures that traditionally have been handled by people are becoming increasingly codified as software agents. Automatic collaborative filtering systems (Shardanand and Maes, 1995) and expert finder systems (Lieberman and Vivacqua, 2000) are serving in roles that used to be primarily the domain of friends and associates. E-commerce agents are doing financial work that used to be done by humans. As agents take over more complex relationships from people, it will become necessary to integrate the hierarchical social knowledge that people use in everyday life – ideas of social dominance and submission. We all use and understand the subtle cues that inform us of where we stand with respect to each other (e.g. body language while haggling). We all make alliances to achieve mutual benefit (e.g. buyers' collectives). Soon, our agents will too.

In order to understand how we might create multi-agent systems with some of the affordances of our complex human social hierarchies, it makes sense first to look at simpler systems that occur in nature. By providing examples from the social hierarchies present among gray wolves (*Canis lupus*) and among chimpanzees (*Pan troglodytes*), we hope to explain how dominance hierarchies occur in the wild, what purposes they serve in that environment, and how that understanding might be applied to the domain of multi-agent systems.

Wolves have hierarchical social relationships; the 'alpha wolf' has first access to food and reproductive opportunities (Mech, 1970). At first glance, this seems unfair to lower ranking wolves. However, it is far more efficient than having lengthy fights every time two individuals want the same thing. Ultimately, if the wolf who *would have lost* the fight is willing to capitulate, the result (in terms of who gets to eat first) is the same, and both wolves are spared the significant costs (in terms of energy, time and potential injury) associated with having an actual fight. Dominance hierarchies are a technology for efficiently arbitrating among individuals who are able to remember previous interactions with other individuals.

Wolf societies are not always strict hierarchies, though, which makes the interactions more complicated. Two lower ranking wolves will sometimes work together to overcome a rival who would be more powerful than either one individually. Not only do dominance hierarchies allow efficient arbitration of competitive situations, but they also provide a strong incentive for the formation of alliances. Similar themes of dominance and submission exist in chimpanzee societies as well (Goodall, 1986). In particular, alliances make up a very strong component of chimpanzee social life.

There are several main ways in which these themes can be applied to multi-agent systems. Dominance hierarchies can be used to streamline negotiations among agents who have already established a relationship in the past. Social status can assist in the formation of alliances among agents who might mutually benefit from some kind of collaboration. Finally, an appropriate representation of dominance and submission can help humans interact with a system.

To implement a social hierarchy, there are three main aspects that must be considered. First, each agent that will be participating in the hierarchy must have some internal representation of other individuals and the relationships that it has developed with them. Second, the individuals must have some means by which to communicate their perception of the social relationships to the other members. Third, the agents must have some desire to achieve its goals or advance itself in the social hierarchy, otherwise there will be no motivating force to drive the system. If each member is trying to get ahead, has a conception of its relationships and is able communicate that conception to others, social hierarchies will result.

Turning to biology for inspiration in technology is nothing new. Multi-agent systems have looked extensively at models of social behavior in the natural world (see Related Work section). Dominance hierarchies are valuable in natural systems (and in engineered systems as well, as we will show) as an effective means of addressing certain issues that come up in the course of social interactions among intelligent entities. Also, people are accustomed to thinking in terms of social status. These two elements combine to make dominance and submission a significant addition to the toolkit of designers of multi-agent systems.

II Related Work

Many studies have been done on the social behavior of wolves. The most substantial course of research has been done by L. David Mech (Mech, 1970), (Mech et al., 1998). Other substantial studies of wolf social behavior have been done by Zimen (1981) and Fox (1971).

With respect to chimpanzees, Jane Goodall heads up the longest field study of any animal species in its natural surroundings, in operation since 1960. Her research at Gombe National Park is without parallel. (Goodall, 1986) Richard Wrangham has also done significant work at Kibale National Park over the last thirteen years, particularly with regard to social relationships (Wrangham, 1986) (Wrangham and Peterson, 1996).

Much work has been done in modeling social relationships among agents (Dautenhahn, 1998) (Hemelrijk, 1999) (Nowak and Latane, 1994). Others are exploring the use of computers as social and emotional entities that can interact with people (Picard, 1998) (Reeves and Nass, 1996). Reynolds (1987) also did seminal work in flocking behavior, which focuses on the physical relationships between individuals in a group. Minsky saw the mind as a collection of interacting entities, some of which served the role of managers (Minsky, 1986).

In addition to the references discussed above pertaining to collaborative filtering (Shardanand and Maes, 1995) and expert finder systems (Lieberman and Vivacqua, 2000), it is also appropriate to mention on-line reputation mechanisms (Zacharia et al., 1999) and buying and selling agents (Maes et al., 1999), all of which relate to the implementation of human social affordances in multi-agent systems.

III Dominance and Submission

Among many social species of animal, there have come to exist social hierarchies in which certain individuals are more dominant than others. There are distinct evolutionary benefits to these social structures, as they provide an efficient mechanism for arbitration and negotiation in the distribution of scarce resources. In this section, we will discuss the presence of dominance hierarchies in wolf packs, in chimpanzee societies and in the human business world.

Wolves

Many populations of wolves eat large herbivorous ungulates (e.g. caribou) as their primary food resource. (Mech, 1970) Since these animals are too large to be safely brought down by a lone wolf, wolves usually hunt in packs. These packs are normally family units; a typical pack might be composed of an alpha male and female (the only pair that breeds), several grown children of that pair (who act as aunts and uncles to the alpha pair's pups), a few unrelated adults who dispersed from their natal pack, and the alpha pair's most recent litter of pups.

With so many members of the pack all striving for the same resources (the right to breed, access to the choicest parts of a freshly-killed caribou), there is inevitable competition among them. However, it is not practical to fight for these resources on a frequent basis, since there are significant expenses associated with fighting (energy expenditure, time, potential injury) for both winner and loser. Social status hierarchies remove the need for constant fighting, replacing it with relatively long periods of static relationships (an alpha individual may hold its tenure for several years) punctuated by periodic reevaluations (as individuals grow up, age, or make new alliances).

These hierarchies are maintained on a regular basis by means of expressive behaviors that communicate an individual's perceived rank relative to another individual. Dominant wolves stare straight at their inferiors with erect fur, ears pushed forward and a highly-held tail. Submissive wolves crouch or roll over, with ears held back and tail curled between legs. These behaviors are derived from other behaviors that reflect *actual* relationships rather than *constructed* relationships – they are ritualized forms of combat, and ritualized versions of infant and juvenile behaviors (e.g. food begging). Vocalizations also play a

significant role (although a human-level language is clearly not necessary for dominance cues to be given and received).

If an individual feels that the social hierarchy is no longer a valid representation of the reality of the power structure, he has only to withhold his submissive behaviors, and a fight with a more dominant individual will almost certainly ensue. Periodically it is necessary for a dominance hierarchy to be tested in reality (i.e. a fight) in order for all the participants to be willing to agree to it between those tests. The most common periods of testing occur when an adolescent approaches adulthood, or when a dominant individual's ability is compromised by age or injury. (Mech, 1970)

Wolf societies are made considerably more complicated by the presence of alliances between individuals. While the beta male might not be able to depose the alpha male on his own, by soliciting another lower-ranking individual over a period of time, he might gain that individuals support against the alpha. Because of this, deposed alpha individuals often fall far further than beta status in the wake of losing a fight; it is not uncommon for the old alpha to become the lowest-ranking member of the pack.

Chimpanzees

Chimpanzees have equally significant but somewhat less distinct social hierarchies than wolves. While social rank is quite evident in chimpanzee societies, it is expressed in a wider range of behaviors. In addition, larger group size, coupled with chimpanzees' tendency to spend most of their time with a smaller sub-group of the larger social group, leads to more complex interactions as the presence of different individuals alters the power structure in the sub-group. In her book *The Chimpanzees of Gombe*, Jane Goodall discusses the social dynamics that are central to chimpanzee societies. "The outcome of an interaction between two individuals (and sometimes the course of their relationship) may be significantly altered by the participation or intervention of a third." (Goodall, 1986, p.174)

As among wolves, social rank appears to be sought after as an end in itself. Although rank may only be evolutionarily valuable because of the resource access that it provides, individuals have been selected who pursue rank for its own sake, and enjoy resource access as a side effect of their social-climbing. As Goodall says, "a characteristic shared by most male chimpanzees is the preoccupation, from adolescence on, with maintaining and bettering their social rank, and many of their interactions are devoted to this end." (Goodall, 1986, p. 184)

Both wolves and chimpanzees maintain separate dominance hierarchies among males and females. However, whereas with wolves the sexes are "separate but equal", in chimpanzees the adolescent males pass to adulthood by first dominating all the female members of the troop. However, there is some crossover between the two dominance hierarchies; for example, the support of a high-ranking mother is often important in the early stages of an adolescent male's climbing of the social hierarchy, and adult females will often seek alliances with high-ranking males for protection and food. (Goodall, 1986)

Human Business

Businesses have many analogs of these social hierarchies, especially with regard to alliance formation. Just as two adult male chimpanzees may team up on a third individual, more powerful than either, and defeat him, two or more companies often bundle their products together to provide added value to the consumer and therefore win greater market share. For example, Microsoft and Intel dominated their market during much of the 1990s as a result of their alliance. "The sheer muscle of the so-called Wintel (Windows-Intel) combine, analysts say, has kept any other computer architecture or operating platform from thriving to a degree that would even remotely threaten its dominance." (TCS Global News, 1996)

In the business world, as in the natural systems described above, there is an expensive switching cost associated with overturning the dominance hierarchy. Whereas a wolf has to spend energy and runs the risk of injury, a company that decides to switch operating systems has to put in quite a bit of effort and runs the risk of significant problems in the process. This acts to keep a given dominance hierarchy in place, rather than encouraging dithering between two closely matched alternatives. The high cost of switching is enough to outweigh the small advantage to be gained by a product that is only marginally more valuable to the consumer.

In both animals and businesses, the sheer fact of being dominant makes an individual a valuable alliance partner. Therefore, dominance tends to be self-reinforcing. This, too, leads to a preservation of the current structure.

IV Application to Multi-Agent Systems

There are three main areas in which dominance hierarchies could enhance a multi-agent system – as a mechanism for negotiation, as a means of forming alliances among agents, and as a technique for portraying a system in a way that is understandable to people. Each of these is discussed in greater detail in the sections below.

Streamline Negotiations

In multi-agent systems, various autonomous entities are trying to accomplish their goals at the same time. However, they must do this in an environment constrained

by limited resources (e.g., computing power, file access, real world resources, money, etc.). Negotiation of some sort occurs to decide which of the agents can access those resources. While the agents in a multi-agent system may not be empowered to hurt each other (as a wolf might harm another wolf), there is nonetheless the possibility of a complicated negotiation process. This is especially true in a dynamic system where goals and resources are rapidly changing. Implementing the ability to develop dominance hierarchies is a mechanism by which to streamline these interactions.

Current multi-agent systems have one significant difference from animals and traditional businesses. They are generally much less tied to the real world, since most of their existence is virtual. Whereas animals have bodies and companies have employees and factories, multi-agent systems have only the computational engines on which they run to tie them automatically to the real world.

With regard to a closed system in which there is no significant connection to real-world resources, there could still be reasons to incorporate a model of dominance and submission. For example, a group of agents all of whom touch the same files might need to decide which of them have the highest priority of access to those files. Imagine that agent A is assigned a priority of 0.9 (because the creator of the system decided that it was the most important single entity), and agents B and C are assigned priorities of 0.8 and 0.7, respectively. Imagine too that agents B and C are able to touch the files simultaneously without causing conflicts, and neither one is able to touch the files without conflicting with A. It might be more efficient to let B and C take priority over A if they are both ready to access those files, even though A has the highest priority of the three. A might even withdraw from the negotiation if it is aware that B and C outrank it as a cohesive unit. Just as an alpha wolf might lose his place at an caribou carcass if two lower ranking wolves team up against him, the most important single element of a multi-agent system might lose its place at the resource trough if two less important elements that know they work well together are both interested in those same resources.

Alliance Formation

While the example above is used to show how dominance hierarchies can be used to facilitate arbitration among competing agents, it also shows how social hierarchies encourage the formation of alliances. To provide an example from the real world, mercata.com is a system of agents that forms buyers' cartels, buying in volume to reduce prices for the customers. This system benefits from the linkage to the real world, where paperwork, packing and shipping costs make up a significant portion of the final price of an item. A system that conceived of cartels as alliances in the context of dominance hierarchies, bringing together many low-ranked individuals to increase their collective clout, might be more effective at finding such benefits, especially in the context of longer-term interactions, where individuals and businesses buy and sell from each other on multiple occasions.

Companies often attempt to form alliances with individual consumers (e.g. free cell phone when you sign up for a six month service plan). Systems of interacting agents will exhibit similar behavior, making a complex web of interconnecting agreements and alliances to maximize their actual and potential resource access. Status hierarchies could certainly be implemented in simple systems, as ways of representing simple dyadic relationships. In addition, they are useful in triadic and more complex interactions. Digital systems, with their great capacity for processing and remembering, could extend their skill in this domain far beyond that of humans, who can only keep track of a relatively small number of interactions at the same time.

Human Interface

In addition to making negotiations among the elements of the system more efficient, and facilitating alliance formation, there is another significant benefit that we see resulting from social hierarchies in multi-agent systems. Since human societies also have clear-cut status hierarchies (e.g. the military and most corporations), we are readily able to conceive of dominance relationships. Therefore, multi-agent systems that present themselves as socially hierarchical would be more readily understood by people. As machines become more complicated, people begin to treat them as intentional beings (Dennett, 1987). Endowing agents with the ability to understand dominance hierarchies and communicate that understanding to people will make it easier for people to comprehend their actions and "see where they're coming from." Social hierarchies could be an effective design and visualization tool, as well as an internal mechanism.

V Implementation

Now we turn to the question of how to implement these systems. Just as with animals, each individual may have its own representation of its environment, but there needs to be some common mechanism by which it communicates with the other individuals that it encounters. In addition, the individual agents need the desire to achieve their goals, or alternatively the desire to advance in the social hierarchy, in order to provide the competitive scenario in which negotiation and alliance formation can occur.

Representation

In an animal hierarchy, there is no outside authority dictating the relationship between individuals. All relationships are maintained inside the heads of the animals. This distributed approach seems most

appropriate for a multi-agent system; if new agents are added or removed from the system, each individual can establish relationships with them as they come on line. This should create a system that is more robust and adaptable that a top-down approach where social relationships are maintained by a third party. Each individual need only maintain the relationships that are appropriate to its own encounters.

Each agent needs to maintain some model of the important entities that it interacts with. This is not to say that it needs to model every entity it encounters, any more than a person keeps an individual model of each and every ant or beetle that we encounter. It needs some mechanism for deciding which individuals to keep track of, and which to ignore. This is a field of extensive research, too involved for us to consider here.

In a multi-agent system, adaptability may not be at a premium. If this is the case, then a hard-coded dominance mechanism would be in order. However, in systems where adaptability is important, it could be useful to mimic the development period of social animals. Perhaps the development of dominance hierarchies in artificial entities should mirror the development of social competence in young wolves. As a wolf pup grows up, there is a relatively long period of growth and learning during which its actions are tolerated to a great degree by the adults of the pack. During this period, the pup can explore the space of expressive behaviors at its disposal, and establish means of interacting with the other members of the pack. While this is not, in itself, a time of efficiency, it allows the development of relationships among the members of the pack. This is similar to the exploration versus exploitation tradeoff discussed by Pirolli and Card (1995). The fact that this period of experimentation exists demonstrates that the benefits gained by the development of strong and appropriate social bonds is more valuable, evolutionarily, than the energy costs of having a more instinctual but less adaptable system.

A similar development period in a multi-agent system would allow time for new agents to "get up to speed." During this period, a new agent brought into the system would be able to try different configurations (e.g. running simultaneously with each other component to determine if there is any change in performance as a result), would be tolerated by the other elements, but would be prevented from experimenting in domains where it could do any real damage. By this means, dominance relationships and alliances could be formed which would optimize the system as a whole. Ultimately, a multi-agent system can be seen as an evolutionary system where performance (or human satisfaction) defines the fitness function. Allowing dominance and submission to develop in a system could be a means to hill-climb on an evolutionary fitness curve.

Communication

In animals, the behaviors by which individuals communicate their perceived social roles are derived from behaviors that originated for other purposes. (Pulling the lips back from the teeth, which originated as a means of not biting one's own lip when attacking another individual, serves equally well as a demonstration of one's *intention* to bite). However, in an engineered system, it is probably easier to create a mechanism of communication among the various agents from scratch, rather than trying to build into each agent a means of perceiving the actions of the other agents. A system designed to communicate efficiently will probably be more effective at conveying information with a minimum of effort than a system which has to co-opt already existing behaviors.

If the agents inside the system are not going to interact with any other systems or with people, then it might be appropriate to write a system that is fitted for their task, having as many or as few signals as is necessary to establish the relationships of the components. If, however, the system should be comprehensible to people (for example, a military simulation in which people are trained in the proper ways of addressing superior officers) then the communication mechanism may be constrained to mimic human interactions to a greater or lesser degree.

Desire

In order for a system of dominance to be relevant, there need to be multiple entities in competition with each other. In a system with unlimited resources, there would be no need to have social status, since the needs and wants of every individual would be met. However, as in real life, there are always limited resources of some kind. Agents are usually created to achieve some goal (e.g. to purchase a given item as cheaply as possible, or to create an impression in the mind of a human observer). Therefore, they have a built in "desire" to do the job for which they were designed. When two agents both want the same thing, a situation is created where a dominance hierarchy could come into play.

VI Conclusion

As social mammals, people are well-versed in navigating complex social environments. We have many words for this arena: we flatter, plot, help, beg, oppress, follow, lead. Autonomous agents know little of this, though. They're only just beginning to recognize each other. However, agents are become competent, even relied upon, to do many things that used to be exclusively done by people. Soon, they will need social competences to go with their computational acumen; they will need to be able to participate in dominance relationships with people and with each other.

We have presented some of the issues involved with bringing social hierarchies into the realm of multi-agent systems. We have used examples from the animal world to pinpoint the most salient causes and effects of dominance and submission behaviors. We then showed how this related to several domains where it could benefit multi-agent systems. Finally, we presented ideas about how social hierarchies might be implemented among agents.

As computational agents take a greater role in negotiating on our behalf in all sorts of ways, it will become important for them to be skilled in the arts of dominance and submission, of alliance formation and assessment, if they are to compete at a high level with other agents and with people.

VIII Bibliography

Dautenhahn, K. 1998. "Grounding Agent Sociality: The Social World is its Own Best Model." *From Agent Theory to Agent Implementation, a symposium at the 14th European Meeting on Cybernetics and Systems Research.*

Dennett, D. 1987. *The Intentional Stance*. Cambridge, Mass.: MIT Press.

Fox, M. W. 1971. *Behaviour of wolves, dogs, and related canids.* Harper and Row, New York.

Goodall, J. 1986. *The Chimpanzees of Gombe: Patterns of Behavior*. Cambridge, Mass.: Harvard University Press.

Hemelrijk, C. K. 1999. "Effects Of Cohesiveness On Inter-Sexual Dominance Relationships And Spatial Structure Among Group-Living Virtual Entities." *Fifth European Conference on Artificial Life* (ed. D. Floreano, Nicoud, J-D., Mondada, F.): Springer Verlag.

Lieberman, H. and A. Vivacqua. 2000. "Agents to Assist in Finding Help." *Proceedings of CHI '00*. ACM Press.

Maes, P., R. Guttman and A. Moukas. 1999. "Agents that Buy and Sell: Transforming Commerce as we Know It." *Communications of the ACM*, March 1999 Issue.

Mech, L. D. 1970. *The Wolf.* University of Minnesota Press.

Mech, L. D. et al. (eds.) 1998. *The Wolves of Denali*. University of Minnesota Press.

Minsky, M. 1986. *The Society of Mind*. New York: Simon and Schuster.

Nass C., Y. Moon, B. J. Fogg, B. Reeves and D. C. Dryer. 1995. "Can computer personalities be human personalities?" *International Journal of Human-Computer Studies, vol.43, no.2, Aug. 1995, pp.223-39. UK.*

Nowak, A. and B. Latané. 1994. "Simulating The Emergence of Social Order From Individual Behaviour" in N. Gilbert and J. Doran (eds.) *Simulating Societies: The Computer Simulation of Social Phenomena* (London: UCL Press) p. 63.

Picard, R. 1998. *Affective Computing*. Cambridge, Mass.: MIT Press.

Pirolli, P. and S. Card. 1995. "Information Foraging in Information Access Environments." *Proceedings of ACM CHI '95 Conference in Human Factors in Computing Systems*. ACM Press.

Reeves, B. and C. Nass. 1996. *The Media Equation*. Cambridge: Cambridge University Press.

Reynolds, C. W. 1987. "Flocks, Herds and Schools: A distributed Behavioral Model." *Computer Graphics*, 21(4) *(SIGGRAPH '87 Conference Proceedings)* pp 25 - 34.

Shardanand, U. and P. Maes. 1995. "Social Information Filtering: Algorithms for Automating 'Word of Mouth'." *Proceedings of CHI '95*. ACM Press.

TCS Global News, 1996. http://www.telecoms-mag.com/marketing/articles/aug96/globe.html (viewed: 6/20/00)

Wrangham, R. W. 1986. "Ecology and social relationships in two species of chimpanzee." pp. 352-378 in D. I. Rubenstein and R. W. Wrangham (eds.), *Ecological Aspects of Social Evolution: Birds and Mammals*. Princeton: Princeton University Press.

Wrangham, R. W. and D. Peterson. 1996. *Demonic Males*. Boston: Houghton Mifflin.

Zacharia, G., A. Moukas, and P. Maes. 1999. "Collaborative Reputation Mechanisms in Electronic Marketplaces." *Proceedings of the Thirty-second Annual Hawaii International Conference on System Sciences (HICSS-32)*, Wailea Maui, HI. IEEE Comput. Soc., January 1999.

Zimen, E. 1981. *The wolf: a species in danger*. Delacorte Press, New York.