Division of Labor in Honey Bees
and
Distributed Focus of Attention

Scott Reed and Victor Lesser

Computer and Information Science
University of Massachusetts
Amherst, Massachusetts

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1.0 INTRODUCTION

A honey bee colony exists in a dynamic environment, subject to slow, seasonal changes in climate and transient variations in local weather and food supply. Overall colony behavior must adapt to these changes in a manner fitting the state of the hive and the worker population. The colony is composed of many individual workers which can engage in such activities as rearing brood, cleaning and building comb, foraging for supplies, or storing and transporting supplies in the hive. At any moment in time, the workers will distribute their efforts over the range of possible activities. Division of labor is the naturalists' term for this distribution and the control process that generates it.

The problem of finding the appropriate division of labor and then implementing this policy in a honey bee colony is an interesting control problem because the workers have a significant degree of local autonomy. Mechanisms are required for detecting that a change in policy is required, for computing a new policy and then for implementing it. These mechanisms are decentralized and robust while at the same time sensitive to both long and short term characterizations of the colony state. The same types of control mechanisms are also needed in distributed, computer, problem-solving systems in which it is necessary to maintain global coherence among a set of cooperating but self-directed processing elements. It is our view that the mechanisms by which division of labor is controlled in honey bee colonies can be generalized and applied to the coordination of self-directed elements in a distributed problem-solving system.

We call the class of distributed computer problem-solving systems which are composed of self-directed elements, sharing the same overall goals, cooperative, distributed systems (CDSs). CDSs are of interest due to their potentially low communication requirements and their robustness [Galbraith 1973 and Lesser and Corkill 1981]. These systems are naturally conceived as being synthesized from many completely equipped processing elements, just as we perceive honey bee colonies as being composed of relatively self-sufficient workers. The largely self-directed nature of processing in a CDS allows processing elements to handle missing information locally by doing the best they can with available data. Because elements keep working without complete information, inter-element cooperation does not have to be highly structured except as the problem to be solved requires it. Another advantage of the self-directed nature of an element's processing is that elements can make local decisions to take on extra work when a nearby element fails, degrades or becomes overloaded, or when unexpected, external stimuli are received.

We are especially interested in systems which fit the "functionally-accurate/cooperative" classification [Lesser and Corkill 1981]. In such systems, as in honey bee colonies, processing elements cooperate to find a workable, satisfactory solution to a problem, not necessarily any specific solution. Controlling functionally-accurate/cooperative systems in a decentralized manner is poorly understood but corresponds closely to the problem of division of labor in a honey bee colony. We call such control distributed focus of attention.

2.0 A DESCRIPTION OF DIVISION OF LABOR IN A HONEY BEE COLONY

A fair body of literature exists on the subject of honey bee behavior and division of labor, but a complete picture of the system cannot be drawn directly from available sources. Because our ultimate aim is the design and implementation of actual computing systems, the bounds of verified facts and current theories concerning honey bee behavior are relaxed. Thus some license is exercised in postulating some of the underlying mechanisms in order to develop a complete and operable model. Sources of our information on division of labor in honey bee colonies are listed at the end of this paper in a selected bibliography.

Honey bee behavior does not appear to be very organized when observations are made over a small range of time and/or space. The activities of an individual bee vary widely over time and the bees' rate of progress in specific places is uneven and not always in a forward direction. Coherent activity is primarily observed at global population levels, over significant periods of time and regions of space. The large number of workers (tens of thousands) permits significant smoothing of the overall colony performance over time. [1]

Worker bees are all capable of engaging in any activity, but some activities are performed by some individuals less frequently, thus dividing the labor over the range of possible activities. In the absence of other influences, the activities an individual engages in are correlated with its age. However, some work, such as cleaning the hive or stinging intruders, can be performed by a worker at any age at any time. Given the constraints of physiological and environmental state, each worker may choose among several alternative activities (eg., building comb or collecting nectar) and situations for performing them (eg., comb building sites or flowers). Such choices, compounded by decisions to change physiological state or location in the colony and environment, are the basis of the division of labor at any time.

The evolution of social behavior in bees evidently has proceeded from solitary individuals, to small, disorganized groups and on to more complex, cooperative organizations. Behaviors from earlier stages seem to remain for the most part; individual workers can still survive as solitary bees. Newer behavior patterns which support cooperation among hive-mates seem to be loosely integrated with the old solitary patterns. This leads us to consider the purely self-directed aspects of behavior separately from behavior requiring the presence of other individuals. We distingush, therefore, <u>self-direction mechanisms</u> for division of labor from <u>cooperation mechanisms</u>. In general, self-directed control mechanisms are sufficient to permit each individual to survive alone (meet own needs) and function well (meet colony needs) for short periods of time without aid from others. Cooperation mechanisms are for coordination when and where necessary, such as when a highly productive nectar source is discovered or when disease reduces the worker population.

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[1] CDSs use far fewer processing elements than honey bee colonies, but the accessability of different parts of the problem solving data base is orders of magnitude greater for CDS elements than for individual bees. Thus, similar smoothing over time can be expected with CDSs.

For each element in a CDS, working on its part of the problem, there are usually alternative processing activities which are more or less appropriate, depending on the data and the required accuracy of the results. The best sequences of activities for obtaining a complete solution, using all the elements efficiently, cannot be even guessed at without some information about the data, its reliability, timeliness, etc. Because of this uncertainty, strategies for controlling processing must be adapted as data is worked on and information is acquired. Greatest flexibility is required in real-time systems where new information is continually being received by different elements and processing must "track" the information, much as the honey bee colony (a truly real-time system) adapts to environmental changes.

Data about the problem a CDS is attempting to solve is contained in the system's <u>problem-solving</u> <u>database</u>. The system's solution is incrementally constructed from the data and takes the form of more abstract data (i.e. the solution also resides in the problem-solving data base). Each processing element in a CDS usually has only enough data to solve part of the problem facing the system; the complete solution must be composed from partial solutions constructed by all the elements.

The general analogy between honey bee colonies and CDSs is as follows (see also Figure 1):

<u>Honey Bee Colonies</u>	<u>CDSs</u>
Hive and Resource Sites in the Environment	Problem-solving Data Base (distributed among all the processing elements)
Worker Bees	Processing Elements
A Worker's Resources and Her Local View of the Hive and the Environment	Data Held By a Processing Element
Foraging, Nursing, Building Comb, etc.	Alternative Data Processing Activities (including the acquisition of new data)

This correspondence between honey bee colonies and CDSs is the source of our intuitions as to the suitability of honey bee division of labor for focus of attention in CDSs.

This paper has two parts: the first describes division of labor in a honey bee colony and presents various mechanisms to account for it, the second describes a CDS focus of attention scheme which incorporates analogous mechanisms. We have attempted to extract some general principles from the "choices" made by honey bees in evolving an efficient system for coordinating many workers. These principles are utilized in our CDS focus of attention scheme and are its primary justification.

Self-direction Mechanisms

Individual Maintenance Needs.

Each worker must allocate some time for eating, resting, keeping clean and seeing to other bodily needs. These activities compete with the colony-benefitting activities for the attention of the individual, but they indirectly satisfy colony goals by optimizing individual performance. We assume some mechanism(s) exist for this competition to occur.

Mechanisms Using Direct Observation.

The individual experience of each bee is known to be important and to influence its behavior in complex ways, but the details of this influence are poorly understood. We will assume that these experiences come from bees' observations of their immediate environment and that they are only positive influences, i.e. observing the need for an activity increases the likelihood of engaging in the activity and reductions in likelihood occur as an indirect result of increases for competing activities. This composes the basic mechanism of motivation for a bee to engage in an activity. The more observations of the need for an activity, the more likely that the bee will engage in it or prepare to (intend to) engage in it.

Cooperation Mechanisms

Implicit and Explicit Communication and the Flow of Materials.

An individual bee's decisions can be influenced by communication that modifies her estimation of the colony's needs. Such a control scheme is used in the material supply and allocation process. Materials are distributed via a sequence of interindividual transfers involving several intermediary bees between the foragers, who supply the material, and the final utilizers of that material. The utilizers actually determine the material needs of the colony. These needs are transmitted to the intermediaries indirectly in that utilizers will accept materials only for the activity they are currently engaged in. Intermediaries, in turn, only accept materials which have been easy to unload to utilizers or other intermediaries in the near past. The foragers specialize in one material until it becomes too hard to find an intermediary to accept the material.

Explicit communication (the well-known "dance" [Frisch 1967]) is also employed to redirect the attention of foragers to needed materials. When a forager is having difficulty unloading its goods, dancing bees may be consulted as to the nature and source of materials currently preferred by intermediaries (and therefore needed by utilizers). When it is very easy for a forager to find a bee to accept some material, she may go to the "dance floor" to dance, communicating to other foragers the type and location of the needed material.

Coordinated Adaptation of the General Division of the Labor.

Because the colony's needs change, some mechanism for efficiently changing all the individual worker's decision making is required. In keeping with the seasons, the colony will be involved mainly with rearing brood (spring), building up honey supplies (spring, summer and fall), or over-wintering. During the spring and summer, when foraging is most important, the specific needs of the colony will vary unpredictably, according to all manner of events in the environment. Global shifts in the division of labor occur in response to these types of unexpected events.

One way the adaptation of the colony to environmental events has been studied is by removing from the hive all the workers engaged in an activity such as foraging. In the redistribution that ensues, other unaffected activities do not suffer greatly; all workers do not drop their current work to take up activities in the under-allocated activity class. There is a gradual change in which considerable delays are physiologically necessary before redistribution is complete and during which the need for workers in the affected class is not diminished.

A simple explanation for this smooth, gradual adaptation is that the rate of activity class transition (a geneticly determined, age dependent constant for each individual) varies among the workers such that faster changing workers take up pending activities before the slower ones can change over. Wenner [1961] proposed that a 1st-order Markov process (in which the probability of changing from one activity to another is independent of past experience) could serve to model these phenomena. Such a model can be expressed mathematically, where the probability of engaging in activity(i) at the next point in time is

$$P(i)=P(i/j)S(i),$$

where $P(i/j)$ is the conditional probability of engaging in activity(i) given that the current activity is activity(j), and $S(i)$ is a measure of the stimulus strength for activity(i) in the environment. The $P(i/j)$ distributions determine the expected rates of transition between activities which are different for different workers. The problem with this explanation is that once the distribution of transition rates is determined for each worker, its effects operate no matter what and how much needs doing in the colony. Smoothness of operation of such a static system can be achieved in the face of slow, small changes, but for very sudden or large changes, the delays in changing activities will result in long term oscillations and possible instabilities in the division of labor.

We hypothesize that cooperation mechanisms play a major role in coordinating decisions when there are large, fast changes in the environment, hive or worker population. Our explanation for the adaptive characteristics of the colony response to fast changes is that a mechanism exists for informing the labor force (with little delay) of the intended distribution of labor, a "feed-forward" mechanism, which lowers the sensitivity of workers to stimuli to which other workers are already intending to respond. Oscillations can still occur at the intention level, but because communication is significantly faster than the time taken to realize intentions, convergence to a good intended division of labor will be relatively rapid and efficient.

Information as to the intended activities of the labor force could be transmitted during food exchange. Individual workers can store food in their stomachs to be shared among other workers and food exchanges are frequent events. Specific chemical substances could be associated with, or encode, specific activity classes, such that the relative proportions of these substances in the food can be used as an indicator of the intended distribution of labor. As food is passed about in the colony, each worker adds an appropriate amount of the substance associated with her intended activity class. We shall refer to this scheme as a "pooled-message" mechanism.

Wenner's model can be augmented with a feed-forward mechanism by adding a factor to account for the intended supply of labor:

$$P(i) = P(i/j)(N(i)-I(i))$$

where $N(i)$ is the amount of labor needed for activity(i) and $I(i)$ is the amount of labor intended for activity(i). $I(i)$ is obtained by "pooled-message" and $N(i)$ is obtained by observation of the state of the colony. This model employs not only non-local information in communicating $I(i)$ information but also local information in determining $N(i)$.

Integration of Control in Honey Bees

Genetic factors are important in controlling the activities of the workers to achieve colony goals. We have already noted that genetics is involved in the correlation of age with activity preferences. This seems to be most important when the colony is in a stable state and the nectar flow is plentiful. In this case genetic determination of the rate of development is possible and the distribution of workers across activity classes is affected directly by the length of time spent at each developmental stage. This "steady state" control mechanism is always at work to some extent, but individual control of development is also possible and is exercised when required.

Other genetic factors are involved in "parameterizing" the various control mechanisms. The details of the worker decision processes (such as how observations of the need for an activity increases its desirability) must be assumed to be determined empirically through the process of evolution.

To actually perform any one activity, each bee must choose among the possible activities, by somehow combining the various control mechanisms. To say much more about the individual decision making in honey bees would require a physiological understanding which we do not possess. We shall forgo the hypothesis of any particular details of decision making in honey bees and instead will now present a scheme for focus of attention in a CDS.

3.0 A GENERAL FOCUS OF ATTENTION SCHEME FOR CDSS

We intend to describe a practical application of the honey bee model for division of labor using the language of computer science. Suitable problems for a CDS style of processing are ones which call for a globally satisfactory solution derived from spatially and/or temporally distributed data which is noisy and errorful. Example tasks are image analysis, speech understanding, vehicle monitoring and traffic control. We shall assume that a CDS has been designed and its task has been decomposed into a number of discrete data processing activities.

The task decomposition should be such that the complexity of the activities is 1) great enough to obtain coherence of action, i.e. activities should result in relatively large grain changes to the problem-solving data base, and 2) small enough to provide choices and flexibility, i.e. there should be many ways, involving different elements, to arrive at a solution. The ability of a CDS to reach a solution in many ways permits distributed control strategies to operate statistically and not be concerned with the generation of detailed plans for low level activity. Flexibility and tolerance to variations in sequencing of activities is necessary for elements to maintain autonomy.

Because of 1) the autonomy of processing elements, 2) the incompleteness of the knowledge used by each element and 3) the presence of noise and error in the input data, there is considerable uncertainty about the contribution of the results of any activity to the complete system-wide solution. Such uncertainty makes detailed planning of activity difficult and ineffective. . This applies both to coordination between elements and to planning sequences of activities for individual elements. However, the task is already decomposed so that exact sequencing of activities is not necessary. This suggests that a pragmatic, moment-by-moment approach to decision making can be taken and that consideration of the details of future decisions would be wasted effort. We are not, however, ruling out the use of abstract information about future plans such as I(i), intended labor supply, as discussed in the extension to Wenner's model.

One approach to making moment-by-moment decisions employs an evaluation function to rate alternative activities. Such a function takes an activity (including information as to the situation for performing the activity, the performance situation) and produces a single number, representing the value of performing the activity. Activities and their performance situations are evaluated according to several focusing criteria concerning the goodness of the data to be used, the quality of past results of the the activity, the goodness of the expected results and the need for the results. This evaluation of potential activities, which is done locally by each element, is the most important aspect of the focusing process and provides the medium for controlling focus of attention. Local focusing data bases consist of all information used by an element in evaluating activities, except for information normally available in the problem-solving data-base.

Focus of attention is controlled by:

1. making changes in the problem-solving data base, i.e. adding or removing performance situations,
2. making changes in the focusing data bases,
3. making structural changes in the evaluation function (including the focusing criteria).

An example evaluation function that produces a single "rating" for an activity and the situation for performing it, using simple arithmetic operations on the criteria values, is described in a later section.

3.1 Criteria For Focus Of Attention

Hayes-Roth and Lesser [1977] have proposed several principles for focus of attention in a centralized system. These principles are:

1. Competition - Once a job is done there is little need to do it again, unless it was not satisfactorily completed.
2. Validity - The more confidence there is in the accuracy of data to be processed by an activity, the more it should be considered.
3. Significance - Activities which produce results known to be useful are to be emphasized.
4. Efficiency - Activities which are easy, cheap and usually successful are to be emphasized.
5. Goal Satisfaction - Activities meeting short-term or subsidiary goals are to be emphasized.

We shall relate the principles of Hayes-Roth and Lesser to the various types of evaluation criteria we have distinguished, as we present them in detail.

In this paper, we are principally concerned with the implications of distributing the focusing task among the elements of a CDS. Based on the work of Hayes-Roth and Lesser and on our study of honey bees, we have defined a set of criteria to be used by each element to rate alternative activities. These criteria encompass the principles of Hayes-Roth and Lesser and add to them since focusing in a distributed system involves additional considerations due to a lack of a central "focus of attention" data base that can be referred to by all elements. Because of the lack of a global focusing view, an element may perform an action that looks good from its local perspective but which is globally inappropriate (either not required as part of the solution or already performed by another element). We shall emphasize those aspects of focusing which are particular to CDSs and refer the reader to Hayes-Roth and Lesser [1977] for details of focusing common to both centralized systems and CDSs.

We discussed honey bee focusing mechanisms as being either self-directed or cooperative and we will discuss CDS focusing criteria in the same fashion. Some criteria rate activities by how they look from an individual element's perspective without communication, while others measure how well activities support cooperation with other processors. We call these self-direction criteria and cooperation criteria, respectively. The self-directing criteria and their correlates in a honey bee colony are:

Observed Need Criterion, ON:S - Looks for a high frequency of occurence of situations in the environment appropriate for an activity to be productive. This is like bees doing work they directly perceive a need for in the colony.

Problem-solving Utility, PU:S - Evaluates characteristics of the activity and performance situation, eg,, efficiency, expected goal satisfaction and the probability of obtaining good results. In bees such characteristics would be determined empirically over thousands of years of evolution, whereas for CDSs they are problem dependent, requiring expert knowledge of problem solving in the area concerned.

Focusing Support Criterion, FS:S - Gives weight to activities likely to improve the focus of attention process itself. Similarly, bees spend time getting information to make good local decisions.

Maintenance Criterion, M:S - Emphasizes activities required for maintenance of the element's problem-solving capability. This corresponds to bees taking time to eat and rest.

The cooperation criteria are:

Intended Supply of Labor Criterion, ISL:C - Directs attention to activities in which low numbers of other elements are intending to engage or are already engaged. If many bees are in the process of becoming equipped for nursing brood, fewer of the remaining bees will initiate the same process, even though the need for nurse bees still exists.

Inter-Element Utility Criterion, IU:C - Looks for a high frequency of acceptance of an activity's results by other elements. Similarly, bees finding it easy to interest others in their forage products will keep supplying those products.

We shall present details of these criteria next.

Details of Self-Directed Criteria

ON:S - Observed Need Criterion

A relatively high frequency of occurence of situations in the environment appropriate for an activity to be productive should increase the likelihood of selecting this activity.

Focusing based on this criterion is called "data directed" focusing. Besides simply making activities possible, the situations in the problem-solving data base for performing activities can influence focusing through "mass stimulus effects": activities are emphasized when situations for performing them occur very frequently.

Each element's problem-solving data base contains only a part of the information required to solve the whole problem. This information is used to make on-the-scene focusing decisions. At any one time instant, the density of appropriate situations in an element's problem-solving data base can be used for evaluation of this criterion.

This criterion should also be sensitive to highly infrequent, but critical events in order to quickly respond to them. A single occurence of such events should produce the same ON:S value as many occurences of more ordinary, less critical events.

This criterion corresponds to the "significance principle" and "validity principle" of Hayes-Roth and Lesser.

PU:S - Problem-solving Utility Criterion

> Certain characteristics of an activity and performance situation, eg., efficiency of the activity, goodness of the data and the probability of obtaining good immediate results, should increase the likelihood of its selection.

This criterion is a complex one, highly dependent on the activities that elements can engage in and the specific task of the particular CDS. In honey bees, this criterion would influence specific decisions such as: which flowers to go to, which region of the "new comb area" of the hive to expand, which piece of dirt to remove from the hive, etc. It corresponds to several of Hayes-Roth and Lesser's principles for centralized focusing and is well covered in their paper. While highly important for good focusing, this criteria is the same when used in centralized systems or distributed systems and we refer the reader to Hayes-Roth and Lesser [1977] for elaboration.

FS:S - Focusing Support Criterion

> Activities likely to improve the focus of attention process itself should be emphasized.

Some activities support the focusing task by reducing uncertainty in either the focusing data base or directly in decision making. An activity which achieves the results of other possible activities may reduce uncertainty by reducing the number of alternatives among which to discriminate in the decision process. Activities such as obtaining a pooled-message concerning the intended system-wide focusing priorties or randomly moving around to observe more of the environment and to interact with distant elements, reduces uncertainty by increasing information available for focusing.

process is an example of aggregation of local views to produce a global view of focusing data.

Hayes-Roth and Lesser do not discuss a prediction principle because the system they were working with was primarily data-directed and no mechanisms existed for planning into the future. However, their competition principle is at the base of this criterion, i.e. don't do work others will be doing for you.

An extension of this criterion would rate higher those activities that produce data required to perform activities in which other elements intend to engage.

<u>IU:C</u> - <u>Inter-Element</u> <u>Utility</u> <u>Criterion</u>

A high frequency of acceptance by other elements of an activity's output should increase the likelihood of selecting this activity.

Because elements reach a solution to the overall problem by aggregating each other's partial solutions, a mechanism for coordinating the work going on in the various elements is required. We suggest a mechanism analogous to the interindividual control mechanisms used by honey bees to control the supply of materials in the hive. In bees the types of materials and resources being foraged for are determined by such a mechanism. In a CDS, the types of partial solutions and other information produced and communicated can be regulated in this way.

An element transmits to other, neighboring elements part of its local view of the problem-solving data base, including work it has done. If the information in these messages is useful to other elements, they integrate it into their own data bases and <u>respond</u> <u>with</u> <u>an</u> "<u>acceptance</u>" <u>message</u>. Each element keeps track of the acceptances for each of its more recent transmissions. Activities which produce information contained in more-accepted transmissions are considered more valuable and receive a higher IU:C rating. We shall call this measure of an activity, the "acceptance response count".

Hayes-Roth and Lesser's principle of "goal satisfaction" corresponds closely to this criterion. This principle is a reflection of the frequent occurence in some systems of intermediate goals in the problem-solving process. Because they were only concerned with centralized systems, they suggest a measure of "goal satisfaction" that requires a non-local view of the problem-solving data base. The measure we propose potentially requires only a local view of the problem-solving data base and low bandwidth communication with other elements.

Hayes-Roth and Lesser's "competition principle" lies at the root of the first of these uncertainty reduction processes, i.e. one should eliminate redundant alternatives. The problem of obtaining information about the other elements' focusing does not arise in a centralized system.

M:S - Maintenance Criterion

> Activities required for maintenance of the element should be emphasized.

In honey bees, local maintenance involves satisfying bodily needs. Maintenance may be necessary at many levels in a CDS element. Aside from hardware testing and operating system maintenance, there is maintenance of the problem-solving and focusing data bases, establishment and maintenance of communication links with other elements, etc. These activities may either be scheduled along with other activities which fulfill other criteria (the "non-maintainence activities"), or a higher level of focusing may be used in which non-maintainence activities, scheduled by a "non-maintenance scheduler", are rescheduled together with local maintenance activities.

This criterion is more important in systems which operate continuously (eg., real-time systems) as opposed to those which are used to solve individual, discrete problems, since in the latter case, a great deal of maintenance can be accomplished before and after solving the problem. While maintenance is usually necessary in all systems, maintenance activities should compete more strongly with problem-solving activities in continuously operating systems to ensure reliable operation.

Details of Cooperation Criteria

ISL:C - Intended Supply of Labor Criterion

> Low numbers of other elements intending to engage in an activity should increase the likelihood of selecting this activity.

An important characteristic for each local focusing data base in a CDS with distributed focusing is that it support or include predictions concerning future labor distributions. This is very important in maintaining system stability. A projection of the current global state into the future, based on information concerning the intentions of other elements, can be used to evaluate alternative activities with respect to ISL:C, to achieve system-wide efficiency in adapting to changes both inside and outside the system.

The "pooled-message" coordination mechanism we have proposed for honey bees fulfills this need, where the message is a list of values, one for each activity class, which represent the relative numbers of elements intending to engage in each class. Each element in the system has, in its focusing data base, a copy of the message most recently received, modified slightly to reflect the element's own intentions. The message is sent to another element when requested and perhaps even when not if sufficient time has elapsed since the last transmission. Limitations on the frequency of pooled-message requests may be required to prevent local conditions from overly influencing the message content (for honey bees such messages would be requested primarily by hungry bees). The pooling

3.2 The Local Focusing Data Base Of An Element

The focusing criteria have associated data requirements which are met by each element through 1) internal sources (levels of hunger, fatigue, etc.), 2) monitoring changes in the problem-solving data base, 3) point-to-point interindividual communication and 4) broadcast communication. The nature and source of data are best discussed criterion by criterion:

- For the Observed Need Criterion, ON:S, a history of the problem-solving data base is required.

- The Problem-solving Utility Criterion, PU:S, encompasses a set of "sub-criteria" which require local input as to the state of the problem-solving data base and possibly non-local communication as to changes in the system's goals.

- The Focusing Support Criterion, FS:S, uses internal information from the focusing data base and local observation of peformance situations for competing activities.

- The Maintenance Criterion, M:S, has primarily internal information requirements but maintenance of communication links requires local communication.

- The Intended Supply of Labor Criterion, ISL:C, is based on a measure of the number of individuals intending to engage in each alternative activity class, which requires internal information about intentions and global communication or an approximation such as the pooled-message scheme.

- The Inter-element Utility Criterion, IU:C, requires reception of "acceptance" messages from other elements. Such acceptance messages do not necessarily have to be an explicit acknowledgement but rather can potentially come from observations of what activities other elements are engaged in after they receive a message.

Taken together, these data requirements constitute the focusing data base which each element must maintain. They are summarized in Table 1:

	cooperation criteria	self-directed criteria
internal info.	ISL:C	FS:S M:S
local observ.	(IU:C)	PU:S FS:S ON:S
local comm.	(ISL:C)(IU:C)	PU:S M:S
non-local comm.	(ISL:C)	(PU:S)

Table 1. Information needs of the evaluation criteria. Entries in parentheses are options or alternatives for the cases in which there is a choice.

3.3 An Example Focusing Procedure And Evaluation Function

We shall roughly define here a focusing procedure based on the above discussion. Input to the procedure at any point in time is the focusing data base and a list of the possible activities with the situations for performing them (called activity-situation pairs, or ASPs). An evaluation function, E[ASP], determines a single value for each ASP, called a rating. The focusing procedure's output will be a single ASP which is selected according to the relative ratings of all the input ASPs.

We shall assume that some high level supporting procedures are already defined, including those that evaluate the ASPs according to the various criteria: ON:S[ASP], ISL:C[ASP], IU:C[ASP], PU:S[ASP], FS:S[ASP], M:S[ASP]. A simple example evaluation function is:

E[ASP] = l1*FS:S[ASP] + l2*M:S[ASP] +

(g1*ON:S[ASP] + g2*ISL:C[ASP] + g3*IU:C[ASP]) * PU:S[ASP]

The value of PU:S multiplies the weighted sum of ON:S, ISL:C and IU:C because their values depend on the general problem-solving utility (PU:S criterion) of the specific ASP. The values of the focusing support and maintenance criteria are added in separately to reflect their independence from problem-solving utility.

Notice also that even if IU:C is low, i.e. other elements are not interested in results of the activity, the total value for E can still be large if ON:S and/or ISL:C are large (assuming PU:S is large to begin with). For communication activities, this will result in "murmuring" [Lesser and Erman 1979] or periodically retransmitting messages felt to be important irregardless of other elements' responses (if any). This also provides the basic mechanism for self-directed processing.

The values for the parameters of this function (g1, g2, g3, l1 and l2) are determined by the system designer, probably by experiment, but possibly from knowledge of the criterion functions. It is also possible to use a search technique to find optimum parameter values. Selection of these parameters corresponds to the genetic control of division of labor in honey bee colonies.

At least two methods are possible for using the evaluation function ratings to select an activity. One method simply chooses the highest rated activity and uses an arbitrary rule to break ties. Alternatively, the (normalized) rating for each activity can be used as the probability of it being performed. In this latter case, a random number generator is used to arrive at each focusing decision. While computationally more expensive, the latter method can compensate for small errors in the ratings by not always choosing the highest rated activities.

With this definition of a focusing scheme, the only structural variable is the evaluation function. Combining several criteria into one measure of worth is an important problem we cannot address here. We refer interested readers to Keeney and Raiffa's [1976] book on this subject.

4.0 CONCLUSION

We have discussed the control of division of labor in a honey bee colony and described a focus of attention scheme for CDS elements. Viewing a honey bee colony as a CDS has helped both in generating concepts for focusing in a CDS and in illustrating them. Many of the details of a CDS focusing scheme will depend on the specific CDS application, just as those in the honey bee colony are specific to its role within an ecosystem. The basic structure of the focusing mechanisms, however, can be applied more generally and this is the primary benefit of this study.

Future work along these lines will include the design and simulation of a CDS which utilizes a focus of attention similar to that described here.

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