# Multiple Pheromones for Improved Guidance

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## Abstract

*Synthetic pheromone systems offer great potential for spatial coordination in multi-agent systems. Initial experiments with such a system applied to the control of air operations has identified the concept of local guidance that is critical to designing such a system, and that can be supported by using multiple pheromones with differing characteristics. This paper reviews the basic mechanisms of synthetic pheromones, describes local guidance and how multiple pheromones support it, and outlines design methods to guide system designers in exploiting this mechanism.*

## 1 Introduction

The synthetic ecosystems approach applies basic principles of natural agent systems to the design of artificial multi-agent systems ([4],[1]). Natural agent systems, like social insect colonies or market economies, express system-level features that make them interesting blueprints for industrial applications. Made up of a large number of simple, locally interacting individuals, these systems are flexible to changing conditions, robust to component failure, scalable in size, adaptive to new environments, and intuitive in their structure.

In natural agent systems, large numbers of individuals coordinate their activities in the fulfillment of tasks in stigmergetic interactions through the environment ([3]). The pheromone infrastructure, proposed in [2], enhances the execution infrastructure of our software agents, providing them with an active environment where they may share information. The pheromone infrastructure introduces a spatial structure to the system in which the agents may deposit synthetic pheromones at discrete locations (places) and perceive concentrations of such pheromones.

The internal operation of the pheromone infrastructure aggregates and propagates pheromone deposits by the agents. At the same time, local pheromone concentrations are reduced in strength automatically by the pheromone infrastructure's evaporation mechanism. There are three general parameters specifying a pheromone in the infrastructure: the pheromone's evaporation factor, propagation factor, and threshold. The evaporation factor determines the rate of the decay of the local strength of a pheromone over time. The propagation factor influences the strength with which a pheromone deposit event to a place is propagated to the neighboring places. The threshold is the strength below which the pheromone is ignored by the pheromone infrastructure. The performance of a pheromone-based coordination mechanism in a specific application depends on these three parameters.

Our paper reports a pheromone-based coordination mechanism of agents on a hexagonal grid. Agents of two species live in places on the grid: pumps and walkers. Pumps regularly deposit pheromones at their current place. Potentially, they are able to move independently over the grid, but in this paper we consider static pumps only. The walkers seek to occupy the same places as the pumps, but do not perceive them directly or know the purpose of their movements. Walkers are only permitted to sample pheromone concentrations at their current place and their immediate neighbors. They may not even communicate directly among themselves. This specific instance of the spatial coordination problem arose in the JFACC ADAPTIV project ([5]) in the tasking of air-combats, where a population of Bomber-agents has to find agents of Air-Defense or Ground-Troop units. Similar scenarios occur in civic domains like traffic coordination or manufacturing control.

Section 2 of this paper reviews pheromone mechanisms and defines some formal concepts. Section 3 presents some experimental results from ADAPTIV that focused our attention on two important characteristics of pheromone-based guidance and led us to formulate a preliminary hypothesis. Section 4 reports an analysis that challenges this hypothesis, but suggests an alternative, and describes a confirmatory experiment. Section 5 presents design recommendations for synthetic pheromone systems based on this understanding and Section 6 verifies the predicted performance improvement in a small experiment. We conclude in Section 7.

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# 2 Walking on Pheromones

A pheromone system embodies two sets of dynamics: those of the pheromones themselves, and those of the walkers, which move in response to the pheromones.

## 2.1 Pheromone Dynamics

Consider a stationary pump that deposits a fixed amount $A$ of a pheromone at a fixed rate of one deposit every $T$ unit time. The long-term behavior of the resulting pheromone field surrounding the pump depends on three parameters: the evaporation factor, the propagation factor, and the threshold of the pheromone.

Evaporation and propagation are inspired directly by physical processes in the real world, where they both result from Brownian movement of pheromone molecules. Evaporation models the removal of molecules from a place by Brownian motion. Some molecules settle on nearby ground where they may be sensed by ants. The propagation of deposit events in the pheromone infrastructure reflects this process.

Unlike evaporation and propagation, the threshold is a concession to the exigencies of a computational model. Physical processes in nature have no problem in bouncing a pheromone molecule anywhere on earth from its point of original deposit, but we model the passage of a pheromone from one place to another as a message in an object-oriented program, and the volume of messages would explode if we continued to pass pheromones whose strengths have decayed so far that they have no further practical effect. So, when a place receives a pheromone deposit below the threshold, it changes the local pheromone concentration, but does not propagate it farther.

If a place propagates a pheromone deposit to its direct neighbors, it determines the new deposit strength for each neighbor as the product of the original deposit strength and the propagation factor divided by the overall number of direct neighbors. The strength of a deposit weakens with every propagation step, because the propagation factor is required to be smaller than one.

A deposit at a place changes the local concentration of the pheromone by the strength of the deposit. Without any deposits, the local concentration of the pheromone is continuously reduced over time. The remaining concentration after one unit time is the product of the previous concentration and the evaporation factor of the pheromone.

A more detailed discussion of the pheromone dynamics in the generic pheromone infrastructure is presented in [2] and a forthcoming ERIM technical report.

## 2.2 Walker Behavior

All walkers move on the hexagonal grid in discrete steps. At a relocation moment t and located at an arbitrary place p, a walker selects its next location probabilistically from the set ($C(p)$) of currently available options. $C(p)$ comprises the current place $p$ and all of $p$'s direct neighbors. On the hexagonal grid away from the outside borders, a walker always has seven places ($C(p)=p_1,\ldots,p_7$) from which to choose. The following discussion assumes that the grid is sufficiently large to ignore the special case of places located at the grid's border.

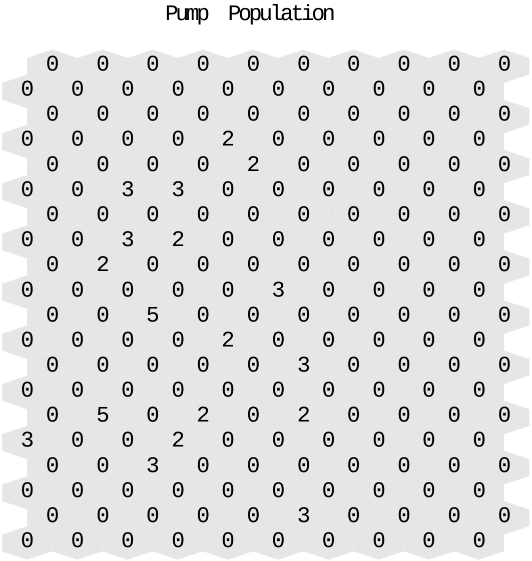
The walker determines the selection probability of the places in two steps. First, it samples the concentration of the pheromone ($s_i$) at each place ($p_i$). In the second step, the walker determines the relative attraction ($f_i$) of a place as its local pheromone concentration normalized by the overall concentration of all places ( $f_i = s_i / \sum_{p_j \in C(p)} s_j$ ).

As a result, the walker has assigned each place a number between zero and one, which add up to one across all seven places. The relative attraction is the probability of a place to be selected. The walker chooses its next place using a roulette wheel weighted according to these probabilities. The *local guidance at place p* available to the walker is $g(p) = \mathop{Max}_{p_i \in C(p)}(f_i) - 1/|C(p)|$, and ranges from 0 (if the pheromone has the same strength in all seven places) to $1-1/|C(p)|$ (if only one place has a pheromone concentration larger than zero).

The pheromone-biased selection mechanism realizes a probabilistic climbing of the spatial gradient of the pheromone field. The stronger the gradient of the pheromone concentration is, the higher is the probability of the walker to follow the gradient.

# 3 Initial Experimental Results

We performed a series of experiments to study the effect of the evaporation and propagation parameters on the local guidance. Figure 1 shows the experimental setup, with 50 pumps distributed randomly in the western part of a 10x10 hexagonal grid.



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3   0   0   2   0   0   0   0   0   0
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 0   0   0   0   0   3   0   0   0   0
0   0   0   0   0   0   0   0   0   0
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**Figure 1. Fifty pumps on a hexagonal grid**

Figure 2 shows a contour plot of the local guidance that results when the pumps generate pheromone deposits with an evaporation factor *E=1/10* and a propagation factor *F=1/10*. The guidance is zero along the eastern portion of the grid, representing a wide valley across which the pheromone cannot propagate and in which walkers receive no guidance. In the western portion of the grid, where the pumps are located, the guidance is highly variable and frequently becomes quite high. If a walker in this region senses low guidance, a short random walk will bring it to a place with high guidance. Thus in this configuration, walkers have difficulty finding a target-rich area, but once within it, can home in quickly on individual targets.

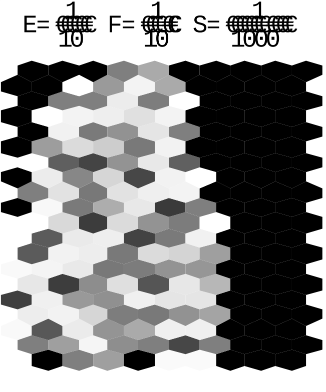

**Figure 2. Local guidance for F=1/10**

Experimentation shows that this picture does not substantially change with *E*. However, it is quite sensitive to *F*, as Figure 3 shows for *F=9/10*. Now the valley is considerably narrower, but the western area is dominated by a crater in which guidance is quite low. In this configuration, walkers can more easily locate the target-rich area, but then have difficulty homing in on individual targets.

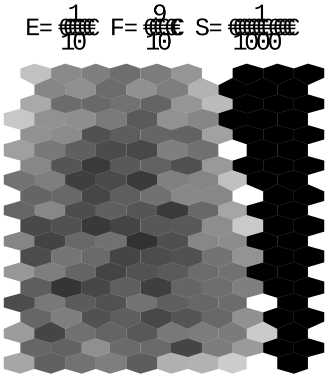

**Figure 3. Local guidance for F=9/10**

These observations led to the hypothesis that a pheromone has an "applicability range," an area on the hexagonal grid where the information in the local pheromone pattern is high enough (by some threshold value) to provide guidance to an agent. The applicability range forms an annulus around the pump (Fig. 4). A walker that selects its new location following the pheromone's gradient when it is too close to the pump or too far away, effectively moves at random.

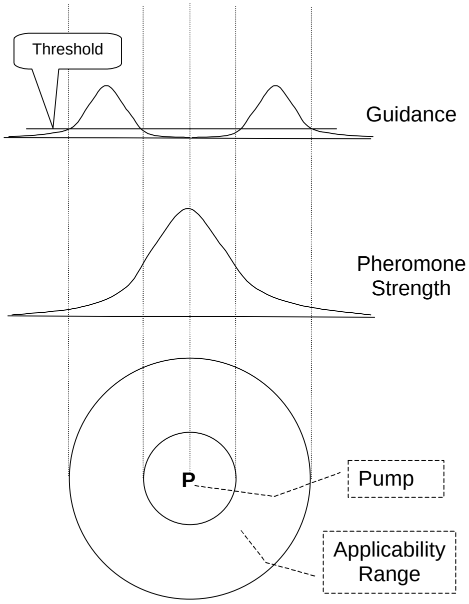

**Figure 4. Hypothesized relation among pump location, pheromone field, and guidance**

We hypothesized that a pheromone's applicability range for spatial guidance depends primarily on the propagation factor of the pheromone. In an area near the pump that creates the pheromone field, propagation loops back through the hexagonal grid to the source through many paths. Thus the reduction in strength of the propagated deposits might be too low to establish a sufficient gradient near a pump, though the pheromone field is high.

Far away from a pump the pheromone field is low and any propagated deposit that arrives there may already have lost too much of its strength to make a difference in the gradient. Then, the applicability range of the pheromone lies in the ring around the pump where the pheromone concentrations change the most with changing distance

## 4 Exploring the Hypothesis

To explore our hypothesis, we constructed a combinatorial analysis of the propagation of pheromones through a hexagonal grid and the guidance that results. This analysis challenges several key aspects of our initial hypothesis, but suggests a new explanation that is confirmed by experiment.

### *4.1 Combinatorial Analysis of Guidance*

To understand what guidance the gradient in the local concentrations of a pheromone actually gives to a walker, we consider the spatial pattern of the concentration of a pheromone around one stationary pump. Assume, that the pump deposits one unit of the pheromone per unit time. This pheromone has an evaporation factor $E \in (0,1)$, a propagation factor $F \in (0,1)$, and a threshold $S \geq 0$. The remaining local concentration of the pheromone at a place after one evaporation step is $E$ times its strength one unit time before. The propagation of a deposit event from a place to any of its direct neighbors in one propagation step is $F$ times the strength of the deposit received divided by the number of direct neighbors, as long as it is larger than or equal to $S$.

#### 4.1.1 Predicting Pheromone Concentrations

The spatial pattern of pheromone concentrations resulting from the pump's activities is symmetrically centered around the pump. Assume that the pump is located at a place $p_0$. On the basis of $p_0$ we structure the places of the hexagonal grid into disjoint sets $P_d$. Each set $P_d$ comprises all places that are reached from $p_0$ in $d$ steps on the shortest path. $P_0$ only contains the pump's place $p_0$, and $P_1$ is the set of all direct neighbors of $p_0$. In general, the set $P_d$ comprises all direct neighbors of all places in $P_{d-1}$ that are neither in $P_{d-1}$ nor in $P_{d-2}$. The set $P_d$ ($d>0$) has $6d$ elements. Altogether, there are $6*(2d-1)$ links from elements in $P_d$ to elements in $P_{d-1}$, $6*(2d)$ links to elements in $P_d$, and there are $6*(2d+1)$ links to places that are $d+1$ steps away from $p_0$.

A deposit of strength one by the pump at $p_0$ triggers a deposit of $F/6$ at every place in $P_1$. A deposit of strength $F/6$ at a place in $P_1$ triggers a deposit of $(F/6)^2$ at $p_0$, at two places in $P_1$, and at three places in $P_2$. In general, a deposit of strength $s$ at a place in $P_d$ triggers a deposit of $s*F/6$ at an average of $(2d-1)/d$ places in $P_{d-1}$, at two places in $P_d$, and at an average of $(2d+1)/d$ places in $P_{d+1}$ ($d>1$). Each propagation step is assumed to take one unit time. The sum of the propagated deposits to a place in $P_d$ $t$ time units after the deposit by the pump at $p_0$ is computed recursively as:

$$q(d,t)=\frac{F}{6}\left(\begin{array}{c}\frac{2d-1}{d-1}q(d-1,t-1)+\\ 2q(d,t-1)+\\ \frac{2d+1}{d+1}q(d+1,t-1)\end{array}\right)$$

Since the pump repeats its deposit every unit time, a place in $P_d$ receives a propagated input of $Q(d,t)=\sum_{j=0}^{t} q(d,j)$ at an arbitrary point in time $t$. Following the analysis of the pheromone infrastructure in [2], the pheromone concentration at a shortest distance of $d$ steps from $p_0$ approaches the fixed point $B(d)=\lim_{t\to\infty}(Q(d,t))/(1-E)$. The graph in figure 5 shows the fixed point of the pheromone concentration on a logarithmic scale for varying distances and propagation parameters with an evaporation factor fixed to $E=1/10$. As a consequence of the cyclic nature of the hexagonal grid, we observe a rapid decline of pheromone concentrations as we move away from the pump.

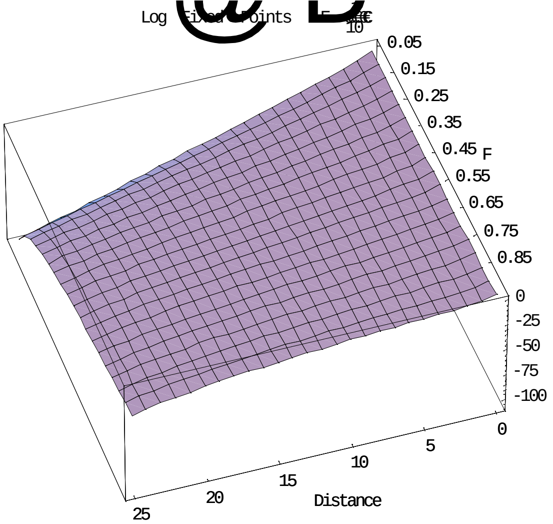

**Figure 5. Fixed points of pheromone concentration (logarithmic scale)**

#### 4.1.2 Testing the Hypothesis

Applying this formalism, we now compute the local guidance available to a walker from a single pump as a function of both distance from the pump and propagation factor (Fig. 6).

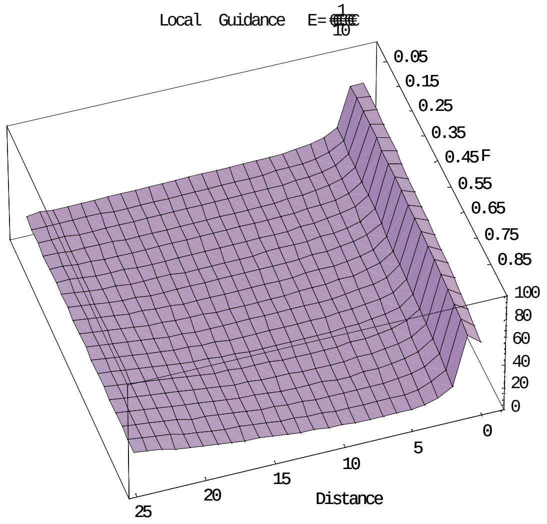

**Figure 6. Local guidance without threshold**

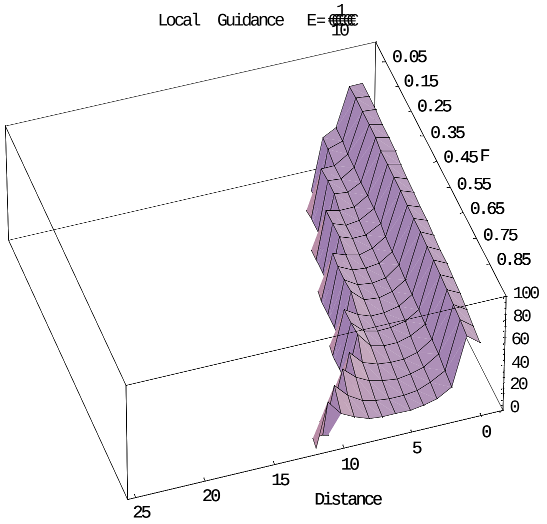

**Figure 7. Local guidance with threshold**

This picture is disconcerting to our hypothesis. A propagation-dependent applicability would appear as a ridge of high guidance, running from (low *d*, low *F*) to (high *d*, high *F*). Instead, guidance is greatest at the pump ($d=0$) or in the places adjacent to it ($d = 1$). Then it drops off rapidly. For low propagation the guidance is fairly constant with *d*. For high propagation, it drops somewhat lower than for low propagation, but only by a factor of two. Then it actually increases with increasing distance. This increase reflects the fact that the local guidance is an approximation of the second (spatial) derivative of the pheromone concentrations. As we see in Figure 5, the decline of the pheromone concentration *increases* with increasing distance.

What then accounts for the behavior we observed in our initial experiments? Those experiments explored the two pheromone parameters inspired by physical analogy, but did not examine the threshold, which we viewed simply as an implementation detail. However, when we apply the threshold to the local guidance, a cliff emerges running from low *d* and low *F* to high *d* and high *F* (Fig. 7). For large F we actually observe an increase in the guidance towards the cliff.

### 4.1.3 Local Guidance in a Field of Pumps

But is the observed increase in guidance towards the cliff at larger distances the predicted applicability range effect? Consider an arbitrary place $p_i$ on the hexagonal grid. The local guidance available to a walker on $p_i$ may be influenced by several pumps. A pump influences the guidance on $p_i$, if the propagation field of the regular deposits of the pump covers at least one of the places in $C(p_i)$, the options in a walker's relocation decision at $p_i$. The radius of the propagation field of a pump depends on the pheromone's propagation factor and the threshold. The last place to receive a propagated input is at a distance of $R_P=ln(S)/ln(F/6)$ steps away from the pump. Thus, if $p_i$ is less than $R_P+2$ steps away from a pump, its local guidance depends at least on this pump's propagation field.

Assume there are currently $n_i$ pumps that influence the local guidance at $p_i$. Then, the influence acts in two ways. On the one hand there is the distance of a pump from $p_i$, which, in relation to the other pumps' distances, determines the strength of the influence of this pump. On the other hand, the location of the place $p_i$ in relation to the nearby pumps also influences the local guidance.

If $n_i$ is zero, then there is no pheromone concentration at any of the places in $C(p_i)$ (assuming the concentrations have reached their respective fixed point). The relocation decision of a walker is a random selection of one of the seven places and the local guidance is zero.

If $n_i$ is one, the local guidance at $p_i$ depends on the distance from a single pump. As we have seen in Figure 7, the guidance has local maxima very close to the pump and at the outer limit of the propagation field.

Finally, if $n_i$ is larger than one, several pumps influence the local guidance at $p_i$. We have been able to identify some scenarios of low or high local guidance, but a complete numerical prediction remains yet to be found.

If the place $p_i$ is significantly closer to one of the $n_i$ pumps than to all the others, the local guidance at $p_i$ is dominated by this nearest pump. In this case the local guidance is predicted as in the single pump discussion. Our observations show that a difference of two or more steps in the distances of the $n_i$ pumps from $p_i$ is already sufficient to return to the single pump case.

If all $n_i$ pumps are about the same distance away from $p_i$, then the local guidance depends on the location of $p_i$ in relation to these pumps. If most pumps are in the same direction from $p_i$, then their effect is again similar to a single pump at the average distance of these pumps. On the other hand, if the place $p_i$ is surrounded by the pumps, their guidance effect is diminished. An extreme scenario, exemplifying this diminishing effect is a pump at each direct neighbor of $p_i$. In this case, the pheromone concentration at six places in $C(p_i)$ is $X$ and at one place it is $Y$, with $X >> Y$. The local guidance is reduced to approximately *1/6-1/7=1/42*.

### 4.1.4 A Confirming Experiment

The previous discussion predicted a primary dependency of the local guidance in a field of pumps on the pheromone's propagation factor $F$ and on its threshold $S$. Secondarily, there is also a dependence on the location of the respective place in relation to the pumps whose propagation field cover the place or one of its direct neighbors. The second influence is only secondary, because it is the radius of the propagation field, determined by $F$ and $S$, that allows multiple pumps to influence a place in the first place.

This observation leads to the following new hypothesis on local guidance and the applicability of a pheromone for spatial coordination:

*A pheromone is suitable for spatial coordination of walkers (high local guidance) in the close neighborhood of pumps (about 5 steps), if it has a small propagation radius. It serves walkers at a medium distance from the pumps (about 15 steps), if it has a large propagation radius. Walkers at larger distances away from any pump cannot be guided by propagated pheromones, because the explosion in the required propagation out to such a distance.*

A small propagation radius requires a relatively large threshold $S$ or a small propagation factor $F$, whereas a large propagation radius is achieved with small $S$ or large $F$. The following figure (Fig. 8) shows the local guidance in the case of our field of fifty pumps for combinations of propagation factors $F=1/10$ and $F=9/10$, and thresholds $S=10^{-2}$ and $S=10^{-6}$. The plots show the best guidance in the regions near the pumps for the configuration $F=1/10$ and $S=10^{-2}$. The best guidance in the medium-distance areas is available for $F=9/10$ and $S=10^{-6}$.

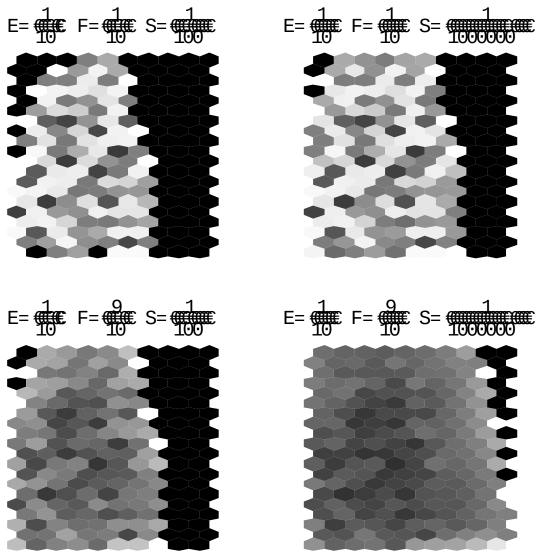

**Figure 8. Local guidance for varying pheromone configurations**

The underlying assumption in the prediction of the local guidance for a specific pheromone configuration is that there is a good guidance at places that are just at the outer limit of the propagation range of a small number of pumps. To verify this assumption, we plot for each place on the grid the number of pumps that are exactly at a distance of $R_P$ from the respective place (coverage). Such a plot should indicate areas of potentially high guidance for a given pump distribution and a specific pheromone configuration ($F$ and $S$). Figure 9 shows the plots for four pheromone configurations.

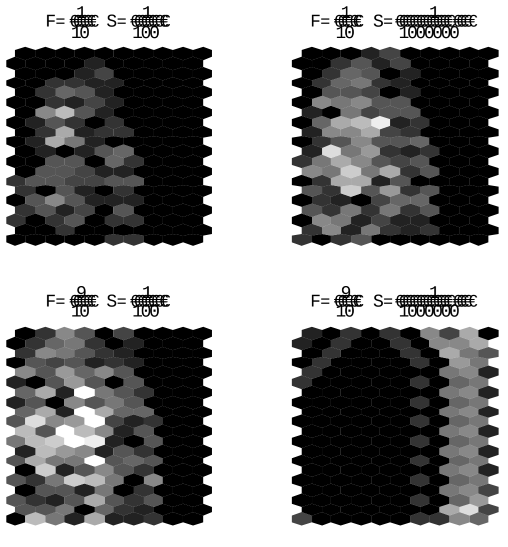

**Figure 9. Local coverage for varying pheromone configurations**

Comparing the local guidance plot of (Fig. 8) with the coverage plots (Fig. 9), we see a link between high guidance and medium coverage of a place. That high coverage does not automatically mean high guidance may seem counter-intuitive at first. But then, with increasing coverage there is also an increasing risk that the pumps are located in different directions from the place. As our previous discussion indicates, pumps at different directions of a place actually decrease the local guidance. The risk of having pumps located at about the same distance but in different directions increases with the number of pumps that significantly influence the local guidance of a place.

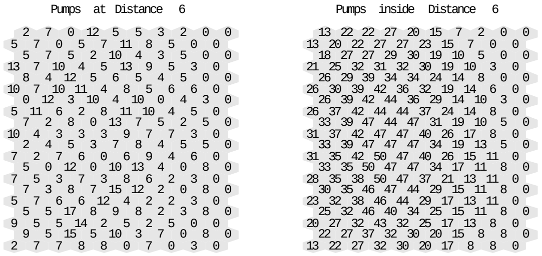

**Figure 10. Influence of pumps at $R_P$=6**

Figure 10 illustrates this effect for a propagation radius of six steps. The left plot shows for each place the number of pumps that are exactly six steps away, while the right plot shows the number of pumps that are maximally six steps away. From the right plot we can derive an indication, where places with good guidance for a pheromone propagation radius of six are. Good guidance is expected to be at places with a small, but non-zero number of influencing pumps. The number may be larger the farther a place is outside a cluster of pumps.

## 5 Configuring Pheromones

The local guidance available to a walker in its relocation decision depends on its current distance to the pumps, the propagation radius of a pheromone, and the spatial distribution of the pumps. Even with stationary pumps, as we have considered them in this paper, it is obvious that one pheromone configuration cannot provide good guidance at all places. We need more variety in our pheromone vocabulary to improve the performance of the walkers.

Our enhanced vocabulary comprises pheromones with different propagation radii. Thus, we have pheromones that provide guidance near the pumps, while other pheromones guide walkers at medium distances. Walkers that are a long distance away from the pumps will have to rely on random walk until we design a different guidance mechanism for them.

The behavior of the pumps and the walkers is adapted to the enhanced vocabulary. Pumps regularly deposit a collection of pheromones, one for each specified pheromone configuration. All deposits have the same fixed strength.

A walker is able to perceive pheromones of different configurations separately. Thus, it is able to decide what pheromone to use for its probabilistic selection in its current relocation step. The walker always follows the gradient of the pheromone that currently has the highest local guidance at the place of the walker. Thus, it will automatically employ the pheromone most appropriate to its current location in relation to the pumps. In addition, the configuration of the selected pheromone allows the walker to estimate its current distance to the pumps.

The choice of the most appropriate pheromone vocabulary is guided by the availability of communication and processing capacity in the execution system, as well as by the typical spatial distribution of the pump population and its relation to the walkers.

The most straightforward choice would be a pheromone configuration for each propagation radius between one and approximately fifteen steps. Assuming all pheromones share the same propagation factor *F*, the required threshold $S_r$ for a given propagation radius *r* is computed as $S_r=(F/6)^r$. However, practically speaking, pheromones with larger propagation radii often convey sufficient guidance at more than one distance away from the pump. Thus, the vocabulary may be reduced to save communication and processing resources.

Figure 11 shows the combined guidance for a vocabulary of six pheromone configurations in the case of our pump population, including pheromones with propagation radii between one and six. As specified before, a walker always picks the pheromone with the maximum local guidance. As the plot shows, now there is good guidance at places near the pumps as well as at medium distance places.

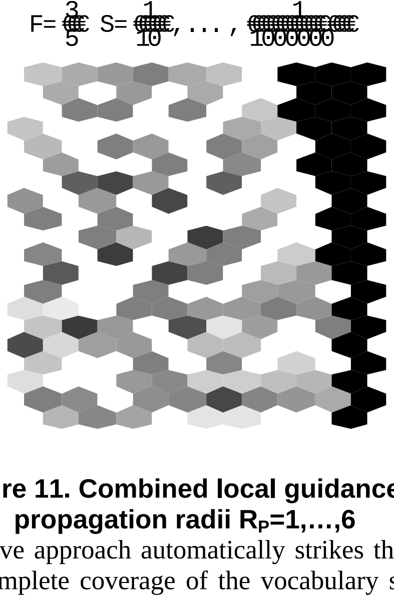

**Figure 11. Combined local guidance for propagation radii $R_P$=1,…,6**

An adaptive approach automatically strikes the balance between complete coverage of the vocabulary space and optimization of the execution performance. Initially, the pumps deposit pheromones configured for all possible propagation radii. In addition to moving towards the pumps, each walker keeps a profile of the usage of the different pheromone configurations, and reports this profile regularly to the pumps it meets. Pheromone configurations that are seldom used either cover areas where walkers never reach, or convey low guidance. Such configurations have a higher chance of being dropped from the active vocabulary of the pumps. To accommodate possible changes in the system's dynamics, configurations that have been dropped are introduced back into the vocabulary at random intervals.

## 6 Experimental Performance Evaluation

Finally, we evaluate the expected improvement in the performance of the walker population. In our experiment we compare the three relocation strategies we presented in this paper. The baseline performance is measured in the random selection of the next location. Then, there is the probabilistic, pheromone-biased selection, always following the guidance of the same pheromone. Finally, we specify six separate pheromone configurations, resulting in propagation radii between one and six. A walker first selects the pheromone with the highest local guidance and then its next location following this pheromone's gradient.

Since different individual walkers move independently, it is sufficient to observe only one of them as it walks over the grid. The walker is placed randomly on the 10x10 hexagonal grid and is permitted to relocate one hundred times. We repeat this experiment one hundred times, each time with a different random seed, to capture statistically significant data.

The pump population of fifty individuals is placed on the grid as in our previous discussions. Each pump deposits a pheromone from each configuration with one unit strength each unit time.

We measure the performance of the walker as the average number of pumps with which the walker shares the same place in each cycle. We call this metric the walker's co-location number.

Theoretically, the best possible co-location number in the chosen setup of the pump population is five pumps, since there are two places with five pumps. But this ignores the random initial placement of the walker, since a walker has to spend some time before it may get to a place with five pumps. Then there are eight places with three and eight places with two pumps.

**Figure 12. Effect of relocation strategies**

In figure 12 we plot the co-location number observed for the three different relocation strategies. In the chosen configuration a random walker shares a place with an average of 0.26 pumps. A walker that always follows the pheromone with a propagation radius of three, shares its place with an average of 1.41 pumps. This is an improvement of a factor of 5.4 compared to the random baseline.

A walker that takes all six pheromones into account, achieves a co-location number of 2.05 pumps. Thereby it performs 7.9 times better than random. The improvement against the one-pheromone relocation strategy is still significant with a factor of 1.5. Thus, the experiment yields the predicted improvement in the walker's performance.

## 7 Conclusion

Pheromone systems are a simple, robust mechanism for generating spatial guidance and coordination among mobile agents. Their robustness is due largely to their nonsymbolic, quantitative nature. Their behavior, like that of other such mechanisms, is sensitive to various tuning parameters.

We have found the concept of "guidance" to be a simple but powerful help in tuning these parameters. This metric, a form of gradient of the field, estimates how much direction the pheromone field gives an agent in deciding on its next step. Common analyses of pheromone fields focus on the absolute strength of the field, but for some purposes the guidance, which can be high where the field is weak or low where the field is strong, is more strongly correlated with agent performance.

Focusing on the guidance metric shows that a single pheromone is a compromise between short-range and long-range direction of a mobile agent. In the context of air operations, for example, a pheromone that can best lead aircraft to the general vicinity of targets will be ill-suited for guiding them to individual targets. Our experiments and analysis show that the best guidance over a range of distances is achieved by using multiple pheromones with varying propagation rates and thresholds. Agents change their focus from one pheromone to another based on which one offers the highest guidance at their current location.

Multiple pheromone methods significantly improve the performance of agents over a range of distances, without compromising the simplicity and locality of interaction that recommend the pheromone approach to spatial guidance and multi-agent coordination.

## 8 References

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