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Andrew P. Black and Mark P. Immel

Digital Equipment Corporation
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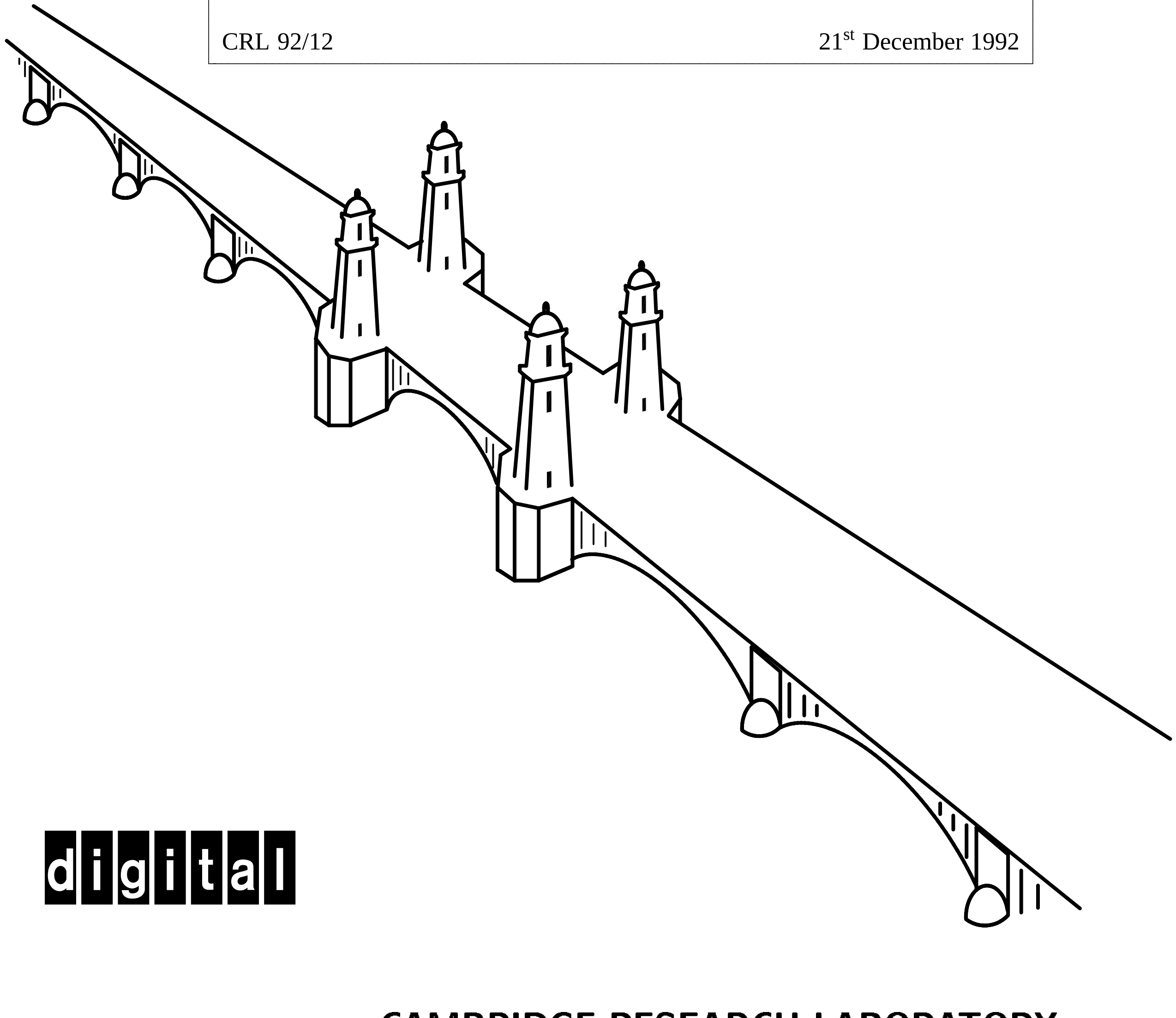

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Abstract

This paper discusses the Gaggle, a mechanism for grouping and naming objects in a distributed system. Using Gaggles, client objects can access distributed replicated services without regard for the number of objects that provide the service. In this way they encapsulate plurality. Rather than imposing a particular design philosophy, Gaggles allow implementors of replicated distributed services full freedom to structure those services as they see fit.

A Gaggle behaves very much like an object: it can be named in the same way as an object, and can be used as the invokee of an invocation. However, Gaggles can be used to represent individual objects, several ordinary objects, or even several other Gaggles, so they serve to encapsulate plurality. If a Gaggle is used as an invokee, *one* of the objects that it represents is chosen to be the receiver.

Keywords: distribution, replication, Emerald, network, object, alias, group, availability, object-finding, wide-area, gaggle, consistency, encapsulation, plurality

Authors' electronic mail addresses: black@crl.dec.com; Immel@das.harvard.edu. Mark Immel was supported by the Division of Applied Sciences of Harvard University while this work was undertaken.

1. Introduction

When designing a distributed object-oriented system, particular choices must be made for the implementation of each object in the system, and for the location of each object. These decisions can have a profound effect on the performance of the system as a whole, and they are therefore likely to be revisited and changed as the system evolves.

A good programming language and development environment will make it easy to encapsulate system components so that the effects of any changes in their implementation are localized. This is true even in centralized environments. The Emerald programming language [6] goes a step further: it also encapsulates distribution. That is, the syntax and semantics (modulo failures) of the basic computational step, the invocation of a named operation on a receiver object, are independent of the location of the receiver.

A particular choice must also be made for the *number* of objects used to implement a particular abstraction. This choice can have a profound effect on the availability and reliability of the system as a whole. However, ordinary objects do not provide a way of encapsulating such a choice. This paper introduces the *Gaggle*, a facility for "encapsulating plurality", i.e., for hiding from a client the *number* of objects that implement a service. The context of this paper is the Emerald programming language, but we believe that the concept of the Gaggle is equally applicable to other environments for the programming of distributed applications.

Gaggles are a low-level tool, in the sense that they do not do very much. The Emerald programming language already makes it possible to implement various replication mechanisms: one simply uses several objects that collaborate (using remote invocation) to achieve the desired effect. We did not wish to duplicate this facility, nor to promote one particular replication mechanism ahead of any other. This is because we view Emerald as a tool for distributed systems research, and our users may well wish to experiment with different degrees of availability and consistency, and different mechanisms for achieving them.

However, the existing Emerald language and model of computation, based as they are on sending an invocation request to a particular object, provide no way of treating a plurality of objects as if they were a single object. Gaggles remedy this deficiency.

1.1. An Example

To clarify the problem, and our proposed solution, consider a highly available file service. High availability is achieved by using multiple servers.

Suppose that there are three servers and that the quorum consensus algorithm is used to ensure consistency [10]. Any object that wishes to read a file must therefore know the set of server identifiers and the algorithm to be followed for reading. We will refer to this information as the access data.

It is possible for every client to have a separate and independent copy of the access data. This has the advantages of simplicity and robustness; provided a quorum of servers is available, the client will be able to obtain service. However, this arrangement has serious maintainability and transparency problems. First, the client must treat replicated files in a different way from non-replicated files. Second, if the replication algorithm is changed, perhaps to the available copies algorithm [2], then every client must be found and modified to reflect that change. In a wide area distributed system this is infeasible.

The obvious solution to this problem is to encapsulate the access data in a clerk object; when a client object needs to read a file, it invokes a clerk, which then executes the read algorithm on its behalf. Now only the clerk must be modified if the access data change. Moreover, if the same clerk interface is used to read non-replicated files, then the representation of a file can be changed from non-replicated to replicated without necessitating any changes in the client.

Unfortunately, using a single clerk reintroduces a single point of failure into the system: if the clerk fails, then the client cannot read its file, even though the file servers may all be available. There are two alternative ways to avoid this loss of availability: *co-location* of the clerk and the client, and *replication* of the clerk.

- If the client and the clerk are *co-located* in the same address space, the clerk is unlikely to fail separately from the client, and the existence of the clerk does not compromise availability. This is sometimes an appropriate arrangement, and Emerald provides various facilities for requesting that objects be co-located. However, it does have significant drawbacks in many situations. If the client is running in a small machine (perhaps a laptop computer), or if it communicates with the servers over a low-bandwith link (perhaps using a dial-up line, or a radio modem), then there are obvious load- and traffic-reduction reasons for locating the clerk near the servers. It is also advantageous to allow many clients to share a data cache kept by a single clerk; in this situation the clerk cannot be local to all of the clients. In addition, initializing a clerk may be time consuming, so that clients that expect to interact only briefly with the file service will be best served by an existing clerk.
- In any of these situation, it may be appropriate to *replicate* the clerk service, and to allow clients to invoke any clerk that is available. A client might pick a clerk essentially at random, or in a way that minimizes response time or that shares the load on the clerks. If the clerk used in the initial invocation is no longer available on a subsequent invocation, the client transparently "fails over" to one of the other clerks.

The Gaggle was conceived as a mechanism for invoking one out of a number of clerk objects. The problem that it solves is fitting the notion of transparent fail-over within a group of essentially equivalent clerks into an object-oriented computation. To understand this problem better, we must briefly look at the primitives of such a computation.

1.2. Characteristics of Distributed Object-Oriented Computation

For the purposes of this paper, we can characterize distributed object-oriented computation by the collaboration of several active *objects* through the exchange of *invocation messages* and replies. Such computations proceed by means of invocations such as

$$\mathit{buffer} \leftarrow \mathit{file}.\mathit{read}[\mathit{offset},\ \mathit{length}];$$

this invocation has four parts. Syntactically, *file* is an expression called the target. Evaluating the target yields the name of an object which we call the invokee. *read* is the name of the operation that the invokee is requested to perform. [*offset*, *length*] is the argument list; the values of the arguments (i.e., the names of the objects to which they are bound) are sent to the invokee along with the invocation request, so that the operation can be parameterized. When the invocation completes, *buffer* will be bound to a result object.

In this computational model, the object that is to receive the invocation – the receiver – cannot be distinguished from the object named in the invocation statement – the invokee. In Emerald, objects are named using network unique identifiers, so the invokee *file* can be anywhere on the network. Moreover, *file* can move from one Emerald node to another: the invocation machinery will track it down. But Emerald does not enable one to express the idea that the invokee should be a plurality of objects.

1.3. Gaggles

A Gaggle behaves very much like an object: it can be named in the same way as an object, and can be used as the invokee of an invocation. However, Gaggles can be used to represent individual objects, several ordinary objects, or even several other Gaggles, so they serve to encapsulate plurality. If a Gaggle is used as an invokee, *one* of the objects that it represents is chosen to be the receiver.

The remainder of this paper is organized as follows. Section 2 characterizes a mechanism for encapsulating plurality that seems to be desirable in our environment. Section 3 discusses other work related to our proposal. Section 4 shows some of the ways in which Gaggles can be used, and illustrates their use in solving real problems of distributed computation. Section 5 looks at the design space for Gaggles, and discusses why we feel that our particular design choices are appropriate. Section 6 describes some possible implementations of Gaggles for systems of various scales. Section 7 summarizes the work and gives its current status.

2. Desiderata for a Gaggle Mechanism

In order of importance, our requirements when designing Gaggles were that they should be a flexible basis for experimentation, that their costs should be appropriate to their function, and that they should fit into the object-oriented model of computation. They should also not detract from the security of a system that uses them. The following sections elaborate on these desiderata.

2.1. Gaggles should be Flexible

Our desire in designing the Gaggle was to create a low-level mechanism that could be used as a basis for experimentation, not a solution to a particular distributed computing problem that was inapplicable to other problems. This is in line with our view of Emerald as a powerful tool for laboratory experiments in distributed computing rather than as a polished product suitable for application programmers. As discussed in Section 3, several group communication mechanisms have been designed with varying degrees of flexibility and scopes of application. We could have simply added some number of them to Emerald as new primitives. But which ones should we choose? Indeed, why should we choose any, when all of them can be implemented using collections of Emerald objects? Instead we designed a mechanism so that once a group communication mechanism has been implemented, it can be packaged as an object and thus conveniently re-used by object-oriented clients.

One measure of their flexibility is whether Gaggles solve problems that we did *not* have in mind when they were designed. In two cases, both of which are discussed in Section 4, Gaggles have demonstrated this degree of flexibility. Whether as yet unthought of uses for Gaggles will be found remains an open question.

2.2. Gaggles should Cost-appropriate

It is naive to require that every facility of a distributed computing environment be fast. Some mechanisms are inherently more costly than others. For example, Bershad has argued that a cross-address space procedure call has an *inherent* cost that is about 20 times greater than that of a local procedure call, while the best implementations of cross-network procedure call are about 100 times as costly [3]. We should not be surprised to find similar differences in the costs of local and remote invocation.

However, we believe that successful mechanisms will have the property that their costs fall almost entirely on those that use them. Programs and components that do not use an advanced facility should not be penalized in order to make it available to other components. The original Emerald work on mobility followed this path; we felt that it was better to increase the complexity and cost of object mobility than to increase the cost of a local invocation by a microsecond or two [12]. Similarly, we hope that adding Gaggles to a distributed system will not increase the cost of unrelated operations at all, and that the cost of a Gaggle invocation will be only marginally more than the cost of an ordinary invocation.

2.3. Gaggles should be Object-Oriented

Since we intend to incorporate Gaggles into an object-oriented environment, they should themselves look like objects. The primitives that can be applied to an object – invocation, **typeof**, **move**, **fix**, and so on – should as far as is reasonable be applicable to Gaggles. Moreover, the semantics of a Gaggle of objects should be such that programmers can think of it as an object. For example, if an object can be added to a Gaggle, then it should be possible to add a Gaggle to a Gaggle. A similar design principle – that a composite (distributed) system should be functionally equivalent to the systems out of which it is composed – was used in the development of the Newcastle connection [9].

2.4. Gaggles should not introduce new security problems

We would like Gaggles to be neutral with respect to security; we do not want them to introduce new security problems, but neither do we expect them to solve existing problems. On the one hand, it is impossible within the existing Emerald system for one object to obtain an invocation intended for another without the cooperation of the receiver; we wish to retain this property. On the other hand, Emerald allows object identifiers to be passed freely from one object to another, so once a server object makes itself known to one client, that client is free to pass the server’s identifier to third parties, which may now invoke the server. The server is free to reject these new request for service, but they cannot be prevented from occurring. (This is in contrast to capability-based systems such as Hydra, in which the capability to call on a service is distinct from the ability to pass that capability to a peer [18].)

3. Relationship with other work

3.1. ISIS Process Groups

ISIS, to quote its developers, is “a system for building applications consisting of cooperating, distributed processes. Group management and group communication are two basic building blocks provided by ISIS” [17]. The system has generated significant interest and is in use at several sites. However, ISIS is not particularly flexible: it presents users with a sharp set of tools suitable for one particular kind of fault-tolerant system, but it is not particularly useful if other kinds of system organization are preferred.

In the most recent formulation of ISIS [16, 17], the sender of a message must itself be a member of a group in order to send a message to that group. This means that an ISIS process group cannot replace a single existing server process directly. If a client wishes to make a request of a server group to which it does not belong, it must send the request to a particular member of the group called the contact, which will generally multicast the request to the whole group. If the contact fails, the client must somehow choose a new contact and and retry the request. Thus the client must be aware of the fact that it is making use of a group of processes rather than a single process: plurality is not encapsulated.

The previous formulation of ISIS [4] had special support for clients of groups. However, this gave rise to significant implementation complexity, and was hard to make secure.

The notion of causal order is central to the ISIS model of computation. Suppose that processes *A*, *B* and *C* are in a group. If *A* multicasts a message to the group, and *B* sends a follow-up multicast, causal ordering guarantees that *C* will not receive *B*'s follow-up until after it has received *A*'s initial message. While such guarantees are sometimes very useful, they are by no means essential for all applications.

Gaggles provide a more lightweight model; using Gaggles, user-level code can simulate all the facilities of ISIS, albeit with some loss of efficiency. A user-level multicast facility will enable most of that efficiency to be regained; such a facility may be included in a future version of Emerald [15]. Gaggles are flexible, cost-appropriate and object-oriented. It seems that Gaggles and ISIS are at opposite ends of a spectrum. In ISIS, every message is multicast to every member, and the messages appear to arrive in causal order. Gaggles do not even guarantee that an invocation will reach any Gaggle member.

An analogy can be drawn here to virtual circuits and datagrams, two kinds of communication protocol. Virtual circuits ensure that packets arrive in order and without duplicates, while datagrams make no guarantees at all. ISIS process groups, like virtual circuits, provide strong reliability guarantees, but at some cost. Gaggles, like datagrams, are simpler to implement and more efficient, but make no guarantees. Continuing the analogy, we note that virtual circuits can be built on top of datagrams, and that causally ordered groups can be built on top of Gaggles. (How this can be done is explained in Section 4.)

It is also worth noting that new applications have revived interest in finding communications protocols that lie between datagrams and virtual circuits. Video, for example, requires ordering but not retransmission of lost packets. We hope that by proposing the Gaggle, a much weaker kind of collection than the process Group, we will encourage other workers to seek interesting points on the spectrum between Gaggles and causally ordered groups.

3.2. Multiple Object Identifiers per Object

While most object-oriented systems provide a single object identifier for each object, there are indications that other alternatives have some advantages.

Reference 5 discusses the possibility of allowing multiple capabilities for each Eden object. Consider a file that can be simultaneously read by multiple clients, and which maintains a file position index for each reader. The file object might create a sub-object for each reader; in this case the current file position index would be implicit. Alternatively, the file might service all of the readers itself, and require that each read request supply a channel identifier. Each of these solution might be appropriate in different situations; however, the interfaces that they present to the clients are different, so it is not possible to mix them freely, or for a file to change from one implementation to the other.

Allowing an object to be known by multiple object identifiers enables each client to invoke a receiver specific to its channel, while still allowing the implementor to choose between the above strategies at will. A single file object known by multiple identifiers could use the value of the invokee to choose the correct channel. Alternatively, the multiple identifiers could be used to name genuinely distinct open file objects.

Gaggles can be used to give an object multiple identities; in addition to its "personal" identity it can have a second identity as part of a Gaggle of objects. To allow an object to have different behaviours when it is invoked in its "personal capacity" rather than as a member of a Gaggle, we have added a language construct that permits an object to distinguish these cases (see section 5.3).

3.3. Multiple Objects per Object Identifier

In Emerald, Gaggles are not the only way in which a single object identifier can refer to multiple Objects. At the implementation level, the Emerald system has always freely replicated **immutable** objects. Immutable objects are often small objects like integers, strings, or types; if a remote node wishes to access such an object, it makes sense to create a local copy for them. Because the state of an immutable object does not change, the implementation is free to create many copies of an immutable object without affecting Emerald's shared object semantics.

User-defined objects can also be declared to be immutable; the system may choose to replicate such objects too. Emerald requires that the *abstract* state of an immutable object not change; it is legal for an immutable object to change its concrete representation. For example, an immutable object that represents a function could memoize its results and still be immutable. If a programmer erroneously declares as **immutable** an object whose abstract state changes, then the result of a computation will depend on the number of times that the object is copied.

Gaggles may be considered as an extension of this mechanism. Invoking a Gaggle invokee is like invoking an immutable object: one of the representative objects will be chosen as the receiver, and the semantics of the computation should be oblivious to this choice.

3.4. Type Restriction

Hutchinson has experimented with an extension to Emerald in which it is possible to restrict the dynamic type of an object[†]. In this extension, the statement

$$\textbf{restrict}\ e\ \textbf{to}\ t$$

denotes a new object that has the same value as *e* but whose type is *t*. It is legal whenever **typeof** *e* – the dynamic type of the object denoted by *e* – conforms to *t*. This means that **typeof** *e* must be more general than *t*; *e* understands more operations, or its operations return more general results. Type restriction is not part of the standard Emerald language, but the same functionality can be obtained using Gaggles.

In Emerald, the the dynamic type of an object will always conform to the syntactic type of any expression that evaluates to it. In symbols, if $\mathcal{E}$ and $\mathcal{T}$ return the value and the syntactic type of their arguments, we have

$$\mathcal{E}[\![\ \textbf{typeof}\ n\ ]\!] \gtrdot \mathcal{T}[\![\ n\ ]\!]\ .$$

This invariant is guaranteed by the Emerald type checker [8]. This means that, in general, if an identifier *n* is bound to an object *b*, only a subset of *b*'s operations will be available for invocation on the target *n*. It is tempting to use this mechanism to restrict the operations that certain clients may perform on a particular object. However, such a restriction can always be circumvented, because an explicit widening coercion (a **view** expression) can be used to transform *n* into an expression with wider type on which all of *b*'s operation can be invoked.

However, Gaggles can be used to achieve the effect of secure narrowing. Consider a Gaggle invokee *B* whose type is a restriction of the dynamic type of an object *b*, and which has *b* as its only member. If the **typeof** primitive is applied to *B*, the result will be the restricted type (as explained in section 5.2), and any attempt to **view** it as a wider type will fail. Any invocations sent to *B* will be received by *b*, since it is the only member of the Gaggle.

4. Using Gaggles

Since Gaggles are quite flexible, they can be used in many different ways. First we describe some of the "usage paradigms" or "idioms" that we have encountered; then we sketch some examples of more complete applications.

4.1. Usage Paradigms

A Gaggle of Independent Objects.

This is the most obvious way of using a Gaggle. A number of equivalent and independent objects are placed in the Gaggle; the client invokes the Gaggle directly for service. A Gaggle of independent objects might be used to access one of a number of equivalent time servers or name servers.

The Consistent Gaggle.

Although Gaggles do not themselves provide any consistency, they can be used to encapsulate the interface to a group of objects that do collaborate to maintain consistency. The replicated file service described in the introduction illustrates one way of achieving consistency. An ISIS-style process group is another way. Because the members of the Gaggle can refer to each other by their own object identifiers, any consistency algorithm of the implementor's choice can be used. Clients of the consistent Gaggle invoke it using the object identifier of the Gaggle invokee.

A Gaggle of Workers.

A Gaggle of objects can be used to encapsulate a pool of worker processes that provide computational cycles for a client. Suppose a Gaggle of *n* objects is created and located on various hosts in order to distribute the computational load. A client object would invoke the Gaggle to initiate work on a particular subtask. Such a request would be received by an arbitrary member of the Gaggle. However, because each member of the Gaggle would be aware of the rule used to share tasks, it would be a trivial matter for the receiver to forward the task to the appropriate worker. For example, the convention might be to assign task *k* to worker object *k* **mod** *n*.

If the amount of data associated with the task is large, this arrangement has the disadvantage that the data must be sent to the receiver and then forwarded to the worker. This can be avoided by not sending the data in the request message; instead the client's name is sent. Once the worker is selected, it can then invoke the client and request its share of the data directly.

Multiple Object Identifiers per Object.

† Norman Hutchinson, Personal Communication.

Gaggles can be used to provide multiple identifiers for a single object. The object simply creates several Gaggles, and then makes itself a member of each. Each Gaggle will have a distinct object identifier. So long as it is the *only* member, all invocations on the Gaggles will arrive at the creating object.

Hiding Object Identity.

It has long been assumed that because the *concept* of object identity is essential to describing the semantics of object-oriented languages, the ability to *test* the identity of two object references is similarly essential. Recently, this assumption has been questioned. The ANSA system [1] does not provide a built-in way of testing object identity at all; if the application demands the ability to test the identity of a certain class of objects, then this can be provided by adding an explicit *getIdentity* operation to the code that defines those objects.

In a system like Emerald that *does* provide testable object identity, Gaggles can be used to hide it, by creating multiple object identifiers for an object, as described in the previous section. While both of these simulations have efficiency problems, they provide an interesting way of simulating a facility that is otherwise unavailable, and thus of experimenting with system design at the user level.

4.2. Some Applications of Gaggles

Accessing a Name Service.

Lampson has described a highly available large scale name service [14] with many servers, each supporting some fragment of the naming tree. A given directory may be replicated on several servers. Each server also keeps information on how to access the servers that serve the parents of its directories.

In order to resolve a name one typically accesses a local server. If that server stores the appropriate directory, it will return the value associated with the name in question immediately. Otherwise, it will return information that will help the requester find an authoritative name server.

Updates are made in a similar way. Because there may be multiple copies of a single directory, and two updates to the same subtree may be received by different servers, it is possible for different servers to present inconsistent views of the namespace. Various algorithms are run on the servers to ensure that all changes will *eventually* be reflected at all concerned servers. However, clients may see temporary inconsistencies, such as a newly-created sub-directory not yet being visible in an ennumeration of the parent directory.

A client of the name service makes use of an object (a clerk) that can provide a single access point for the service. The clerk encapsulates information about the service, such as the identities of the servers that support various parts of the namespace, and may also cache the results of previously submitted queries. The name server clerk deals with an enquiry by first searching its own cache, and if possible returning a result without ever contacting a name server. If no match is found in the cache, the clerk makes a corresponding inquiry of a nearby name server; the clerk would keep information about the responsiveness and location of several servers to ensure a timely response. Updates are reflected in the cache, and forwarded to a server for the appropriate naming domain.

The advantage of such an arrangement is that while the clerk improves responsiveness, it keeps no vital data. There is no need for the clerk to be persistent. If it crashes, the client can use a new clerk. In fact, there will typically be several clerks active at a give time; it doesn’t matter which one the client uses.

This sort of application can be very conveniently implemented by making the clerks a Gaggle of independent objects. Using a sufficiently-large Gaggle helps to ensure that a clerk is always available. Since using the same clerk in successive operations is not necessary for correctness (although it may improve performance), the fact that successive Gaggle invocations may be dealt with by different receivers is not a concern.

Causally Consistent Name Service.

Although the weak consistency of a Lampson-style name service helps to ensure high-availability and low latency, Ladin has observed that sometimes this semantics is inadequate [13]. For example, suppose a system administrator wishes to create a new sub-directory and then to populate it with information about printers. If the update that creates the directory goes to one server and the request to add the first printer goes to another, the operation to add the printer may fail because the directory does not exist. In this situation, high availability doesn't help; the perceived behavior is simply incorrect.

Ladin describes a mechanism that lets the client control the degree of consistency that is required. Each update to the namespace returns an identifier. Enquiries and updates may require that the state on which they operate is "later" than the state created by a certain set of updates; this set is identified *explicitly* by providing the set of update identifiers as an argument to the name server request. Using this mechanism it is possible to state that the various additions to the printer directory must be "later" than the update that created the directory. If such an addition happened to be sent to a server that has not yet seen the creation of the directory (i.e., it arrives too "early"), the addition will be delayed until the server has been able to obtain and apply the update that created the directory. In this way the algorithm achieves tighter consistency, possibly at the expense of longer response times.

A Gaggle of independent objects can be used to provide an interface to a Ladin-style name service just as effectively as to a Lampson-style name service, and in the same way. However, in a small-scale Ladin-style name service, where all directories are fully replicated, the rôle of the clerk in finding an authoritative server for a given operation disappears. Any server will do. In this situation all the servers can be made members of a consistent Gaggle that can itself be the receiver of the updates and queries.

4.3. Mail dispatch

When sending mail, the user agent needs to contact a message transfer agent that is willing to store and forward its messages. Any of a number of message transfer agents will serve.

This problem can be solved by constructing a Gaggle of independent message transfer agents, and invoking the Gaggle to deposit outgoing mail. This Gaggle invocation will succeed if any one of the transfer agents can be found.

5. Design Space

We believe that the design of Gaggles is consistent with the desiderata. However, the path by which we arrived at this design was far from straight. Because some of the side trips help to explain how we reached the final destination, we present both our current design and some of the alternatives we tried along the way.

5.1. Syntax for Gaggles

One of the first issues that must be dealt with is how Gaggles should appear in the Emerald language. In some ways, Gaggles are similar to other forms of collections, like Arrays and Vectors, that are already in the language. Constructors for these collections are presented as Emerald objects. Much of their implementation is also in

Emerald, although some operations must be implemented by system primitives. It seems desirable to present Gaggles in the same manner. This approach minimizes changes to the language itself; the only additions are system primitives.

The object *Gaggle* is similar to *Array*; it is immutable and has the following interface:

function *of* [*AType* : *Type*] → [*result* : *GaggleType*]

The object resulting from *Gaggle*.*of*[*AType*] is immutable and has the following interface (which we will call *GaggleType*)

function *getSignature* [ ] → [*Signature*]
operation *new* [ ] → [*GaggleManager*]

There are two ways of viewing a Gaggle. A *GaggleManager* represents the management interface of the Gaggle, and exports the following operations:

operation *addMember* [*AType*] → [ ]
function *invokee* [ ] → [*AType*]

addMember allows the addition of objects to the Gaggle. *invokee* gives access to the service interface; this looks like an ordinary object with the type given in the *of* operation; naturally, it provides no management functions.

The following code fragment shows how a Gaggle might be populated and used.

const *aGaggleManager* ← *Gaggle*.*of*[*NSClerk*].*new*
aGaggleManager.*addMember*[*NS*.*lookup*[*″primary clerk″*]]
aGaggleManager.*addMember*[*NS*.*lookup*[*″alternate clerk″*]]
aGaggleManager.*addMember*[*NS*.*lookup*[*″backup clerk″*]]
const *aClerk* : *NSClerk* ← *aGaggleManager*.*invokee*[ ]

After this sequence, *aClerk* is bound to the Gaggle's service interface, which can be treated like an object of type *NSClerk*. In particular, it can be invoked; for this reason we call this entity the GaggleInvokee.

5.2. Semantics

In order to make a GaggleInvokee like an object, every aspect of the language that involves objects must be defined for GaggleInvokees.

In Emerald, a program may **move** an object to a location, **fix** an object at a location, **unfix** an object, **refix** an object at a new location, determine the **typeof** an object, **view** an object as having another type, determine whether an object **isfixed**, invoke an object, and **locate** an object. We have devised ways of handling all of these possibilities.

- The Emerald **move** primitive is actually a hint; the implementation is not required to perform the move suggested. Thus, one alternative is to say that move applied to a GaggleInvokee does nothing. But, it is conceivable that the Gaggle would like to take some action when an object tries to move it, such as creating a new member at the specified location. For this reason, members of a Gaggle may provide an operation *move_handler* which takes the appropriate action.

  The semantics for move, when applied to a GaggleInvokee, are to invoke the operation *move_handler* on the GaggleInvokee. If the chosen receiver does not have such an operation, no action is taken.

- The **fix** statement fixes the location of an object; this prevents the object from moving until it is unfixed. Often, rather than specifying a location by means of a node object, the programmer specifies a second object at which to fix the first. In this case, the location of the second object is ascertained, and the first object is fixed at the same location. The **fix** statement fails if the object is already fixed.

Since immutable objects are copied rather than moved, fixing an immutable object is a null operation. The location of an immutable object is always "here" (it is co-located with the enquirer), so fixing an object **at** an immutable object has the same effect as fixing an object at the current location. (At one time we considered creating a special object **everywhere** to represent the location of immutable objects; however, this was never implemented.)

We considered imitating these semantics for Gaggles, but decided against it. Because the number and location of the members of a Gaggle are chosen by its manager, not by the system, there is no guarantee that there will always be a member at a particular location, and it seemed inappropriate to allow the statement **fix** *g* **at** *l* to succeed in spite of the fact that no member of the Gaggle *g* is at location *l*.

The same objection can be raised against another alternative: treating **fix** like **move**, i.e., to say that members of a Gaggle may provide an operation *fix_handler*. Since **move** is a hint, the (user-defined) implementation cannot be "wrong". But **fix**, unlike **move**, is not a hint.

In the end we decided to make it an error to **fix** a GaggleInvokee, or to fix an object at a GaggleInvokee. With hindsight, it might also be wise for it to be an error to fix an immutable object.

- Since it is not an error to **unfix** an object which is not currently fixed, it is not an error to **unfix** a GaggleInvokee.
- The **refix** construct is an atomic **unfix** and **fix**; like **fix** it fails if either the object or location is a GaggleInvokee.
- The **typeof** a GaggleInvokee is the type that was used as argument to the *Gaggle.of* [$\cdots$] invocation that built the Gaggle constructor. **typeof** does not return the type of any particular member, which might be wider (i.e., it might have more operations). This is because the meaning of the statement "object *o* has type *T*" is that all the operations in *T* can be invoked on *o* without danger of a "Message-Not-Understood" error. In the case of a Gaggle, we can offer this guarantee only for the type specified as the argument to *Gaggle.of* [$\cdots$].
- The expression **view** *o* **as** *T* is an expression with syntactic type *T*. At execution time, The system checks that **typeof** $o \mathrel{\geqslant} T$. If it does, the view expression succeeds (and returns the value of *o*). If not, the view expression fails. This rule needs no modification for GaggleInvokees, given the above definition for **typeof**.
- The **isfixed** predicate tests whether or not a particular object is fixed. Since a GaggleInvokee cannot be fixed, **isfixed** applied to a GaggleInvokee is always false.
- Invocation of a GaggleInvokee is defined to be the invocation of some member of the Gaggle, if a member can be found. If no member can be found with reasonable effort, the GaggleInvokee is considered unavailable. The implementation is free to invoke any member, and need not invoke the same object on two consecutive invocations. Our reasons for this choice are discussed in Section 5.4.
- The expression **locate** *o* returns the current location of the object *o*. Evaluation of a **locate** expression requires running the object-finding algorithm normally used for invocation. **nil** is returned if the object cannot be found. For GaggleInvokees, an attempt is made to find some member of the Gaggle and the

location of that member is returned. If no member can be found with reasonable effort, **nil** is returned.

At first glance, this may seem like a rather peculiar semantics for **locate**. Two consecutive **locate** statements could return locations of nodes on different continents. But the same possibility existed before Gaggles, as the object could move between the **locate** statements.

5.3. Other Language Constructs

There is one other language construct, the keyword **self**, which needs to be clarified in the presence of Gaggles. In addition, we have added two new primitives, denoted by the keywords **isplural** and **invokee**.

- **self** always denotes the current object, i.e., the one that executes the **self** statement. In the case of a member of a Gaggle, it does not refer to the Gaggle but rather to the member itself.
- **invokee** denotes the value of the target of the current invocation. An object may need to know if it has been invoked as a member of a Gaggle (and if so, of which Gaggle) or if it is has been invoked under its own name. **invokee** returns the GaggleInvokee if the object was invoked as part of a Gaggle, and **self** otherwise.

  This keyword is permitted only within the bodies of operations. Inside an initially, recovery, or process section the object has not been invoked and thus **invokee** has no meaning.
- **isplural** is a primitive predicate; **isplural** *o* returns **true** if *o* is a GaggleInvokee, and **false** otherwise. Although a client cannot violate the encapsulation of plurality and see the members of a Gaggle, it may occasionally be necessary to know whether or not an object is a GaggleInvokee. The provision of **isplural** is in the same spirit as the provision of **locate**; we expect that it will be used infrequently, but that sometimes it will be required.

5.4. Semantics of Invocation

Every Emerald object may be invoked. It is this feature of the language that makes the addition of Gaggles difficult. Conceivably, when a GaggleInvokee is invoked, the invocation could be sent to one, some, or all of the members of the Gaggle.

Sending the invocation to all members is an unwise choice, because if one member is unavailable the invocation must fail, and one of our goals was to increase availability. A more reasonable choice is to send the invocation to all *available* members; this is the option chosen by the ISIS process group mechanism. However, this means that the implementation must keep a list of currently available members, and that the delivery of invocations must be consistent with this list. In other words, it requires a full implementation of causally consistent groups. Our intention is that the Gaggle should be a lighter-weight mechanism that can be used to *build* causally consistent groups.

Another possibility is to invoke *many* of the members: not necessarily all, but several. This is not very useful; consistency cannot be achieved by this mechanism alone, and having all members that receive the invocation communicate it to all other members would generate an unnecessarily large number of messages.

The remaining alternative is to invoke a single member object. There are motivations for this choice besides the process of elimination: this is all that many applications require (see Section 4), and the other invocation protocols can be built on top of this one. This alternative maintains the requirement that the users of services are the ones who pay for them. In addition, it results in simpler semantics and implementation, and greater efficiency.

5.5. Failure Semantics

With the above semantics for invocation, one should not interpret the fact that the GaggleInvokee is unavailable to indicate that every member of the Gaggle is broken. Indeed, given two simultaneous invocations of the same GaggleInvokee on the same or different nodes, one may fail while the other succeeds.

We have considered allowing an object to retry a failed invocation, while indicating to the system that it should try harder. Objects could thus try increasingly expensive levels of invocation before deciding that the GaggleInvokee is unavailable. Another possibility is to allow invoking objects to indicate the “permissible expense” of an invocation directly. Then, the implementation would try no harder than instructed to locate the object.

5.6. Ownership vs. Multiple OIDs

We explored various alternatives for providing the management and client interfaces before settling on the scheme described above. One alternative was that one member of the Gaggle would be special; it would be the owner of the Gaggle. Only the owner could execute management operations. This design would create a fragile Gaggle in that the owner could crash and incapacitate the Gaggle. We therefore considered allowing the owner to pass ownership rights to other objects.

The ownership concept implied that owners of the Gaggle might not have the same type as other members of the Gaggle, since they would have additional operations for management. What, then, would be the type of a GaggleInvokee? It was this problem that prompted us to conceive our present solution, which creates two object identifiers to differentiate between the two interfaces.

5.7. Types

The type of each member of a Gaggle must conform to the type of the GaggleInvokee. This does not imply that each member must have the same concrete type, or even the same abstract type. This typing rule is the most lenient possible: it is the minimum requirement on the members that ensures that sending an invocation to any one of the members will not result in a “Message-Not-Understood” error.

5.8. Removal and Enumeration

We do not provide these services for Gaggles. To do so would require maintaining a list of all members of a Gaggle and running consistency protocols. The price we pay for our light-weight Gaggles is that these operations are not possible. However, if they are required, these operations can be implemented at the user-level as follows.

An object can forward invocations to another object by making the body of each of its operations invoke the corresponding operation on the other object. Similarly, it may forward invocations to a set of objects by maintaining a list of the objects and forwarding invocations to each. The forwarding object can provide a list of the objects to which it currently forwards (these are the members). If it accepts instructions to update the list, it can also export operations to add and remove members.

However, the forwarding object is a single point of failure. If it breaks, the entire group is unavailable. This can be remedied by making the forwarding object a Gaggle. The Gaggle can also provide the desired removal and enumeration facilities; the members of the Gaggle run their own consistency protocol to ensure that membership changes are seen by all members of the Gaggle. Users of the group invoke the Gaggle, which forwards the invocation to the members of the group.

5.9. Gaggles as members of Gaggles

Since Gaggles are designed to be treated as objects, there is no reason why Gaggles should not be members of other Gaggles. An invocation of a Gaggle can be forwarded to any member, including a member that is a Gaggle. The consequence is that the invocation must eventually be delivered to a member of the transitive closure of the Gaggle that was initially invoked. Since Gaggles have no membership list, we cannot prevent a Gaggle from being (indirectly) a member of itself. This implies that the invocation protocol must detect cycles.

6. Implementation Considerations

Although do not yet have a complete implementation of Gaggles, we have considered many possible implementation strategies and their suitability for systems of varying scale. We are pleased that the design of Gaggles has not made implementation inflexible; indeed, we often found ourselves dazzled by the array of alternatives. Just as it is hard to imagine a single object location algorithm suitable for systems of vastly differing scale, it is unlikely that a single Gaggle invocation algorithm will suffice in all situations. Given some basic constraints, such as the inclusion of protocol version numbers in the headers of messages, there is no reason why the implementation of Gaggles could not be different on different nodes, or be changed dynamically while the system is running.

There are two major primitives to be implemented: adding a member to a Gaggle, and invoking a GaggleInvokee. It seems that there is a tradeoff between work done at the time a member is added and at the time an invocation is made. At one extreme, we could tell every node in the network of every new member. Then, every node would have a complete membership list and invocation would easy. At the other extreme, we could tell no other node of the new member, and to perform an invocation we could ask every node if it knows of any members of the Gaggle.

There is no parallel to the Gaggle *addMember* operation in an ordinary Emerald system. However, we do have experience with various algorithms for finding (singular) objects. An understanding of these algorithms will form the basis on which we can build a Gaggle location algorithm.

6.1. Algorithms for finding Objects

Emerald combines the process of finding an object with the process of invoking it. This is done for efficiency (objects are usually found at their previous location) and for correctness (an object might move between the two stages of an algorithms that first found an object and then invoked it).

The Broadcast Algorithm.

The original Emerald system ran over a five-node local area network at the University of Washington. The identities of the nodes were static and well-known.

If a node needed to invoke an object not present locally, it checked to see if it had a forwarding pointer to the object (a last known location of the object). If it did, the invocation was sent to that node. If the object was still there, the invocation would succeed. Otherwise, the forwarding chain would be followed until either the object was found and invoked or the chain broke.

If the object was found, the invoking node received a new forwarding pointer so that it could update its local tables. If the invoking node had no initial forwarding pointer, or if the forwarding chain had broken, the invoking node used broadcasts and, if they failed, a series of reliable point-to-point messages to all other nodes in the network. The object would either be found, or it would be determined to be unavailable.

Although this algorithm was suitable for a small scale local area area network, it is clear that it will not scale to the wide area.

The Hermes Algorithm.

The Hermes location algorithm was designed for the wide area and does not require broadcasts [7]. Forwarding pointers are still used, but in the event of a broken forwarding chain, the location of the object is obtained from stable storage.

Each Hermes object has a current location and a storesite, both of which may change. The storesite is a stable storage device that preserves a record of the object's state. When an object moves, the node from which the object is moving keeps a forwarding pointer to the new location; in addition, the storesite is informed of the new location. The forwarding pointers are appropriately timestamped so one can tell which of two forwarding pointers is newer. Whenever a reference to an object is passed from one node to another, a pointer to its last known location is passed as well. Thus, when one object invokes another, the Hermes algorithm always has a forwarding pointer to follow. If the chain of forwarding pointers is broken, the location of the object is retrieved from stable storage.

Since the object can change its storesite, finding the current storesite is not trivial. The name of the object's initial storesite is encoded in its identifier. When the object chooses a new storesite, the old storesite is required to keep a forwarding pointer to the new one; the name service is also informed. When the location of the new storesite has become stable in the name service, the old storesite can forget the forwarding pointer.

Modifying the finding algorithms for Gaggles.

It is clear that following forwarding pointers will not work when object identifiers are no longer unique, i.e., one object identifier can refer to many objects. And this is precisely the situation we have created with Gaggles.

One solution is to break the problem into two pieces. First, when a node invokes a GaggleInvokee, it selects a particular member to invoke. Second, the Hermes algorithm is used to find and invoke that member. Unfortunately, this gives up the advantages of the weak invocation semantics of the Gaggle. If the particular member chosen happens to be at the end of a long forwarding chain, the invocation will be slow, even though some of the nodes that participated in the forwarding process might actually host other members of the Gaggle.

The alternative approach – invoking all known members in parallel – violates the semantics of Gaggles. Finding all known members in parallel and then invoking the one that is found first is correct but potentially very expensive. We are forced to see a compromise.

If any known member of the invoked Gaggle is local to the invoking node, the invocation can be performed without further ado. If there is no such member, one of the known members is selected (using the best information that is available locally) and the forwarding chain for that object is followed. However, the invocation message contains not only the identifier of the selected object, but also the identifier of the Gaggle, and a tag indicating that this is a Gaggle invocation. Now the recipient of this message has more freedom of action. If the selected member of the Gaggle is local, the invocation can be performed. If it is not, but some other member of the Gaggle is local, the invocation can *still* be performed. Failing these happy eventualities, the recipient can either follow the forwarding chain for the initially selected object, or it can substitute some other known member of the Gaggle and forward the invocation to it.

Some care must be taken to ensure that this algorithm terminates. It is sufficient to record in the invocation message the most recent timestamped forwarding pointers to all of the members on which invocation has been attempted. In the case of nested Gaggles, this will also serve to detect membership cycles.

The effectiveness of this algorithm depends on the care with which we select the particular member to which the invocation is forwarded at each step. The selection is assisted by keeping as much information as possible about the various members. In addition to timestamped forwarding pointers we might keep information about network topology, system loads, and response times measured on previous invocations.

The initial invoker (indeed, any node on the invocation path) can also limit the flexibility that it grants to other nodes later in the chain by setting a maximum number of forwarding steps; when the maximum is reached, the invocation is forwarded no further, but instead a progress report is returned to the initial invoker containing updated membership information and forwarding pointers. The initial invoker can then decide whether to continue with its first choice of member or to try a different member. (A similar facility appears in the Hermes algorithm under the name of a hop-count; however, since in Hermes the invoked object is singular, the initial invoker has no freedom of choice. However, limiting the length of forwarding chains does increase robustness.)

In general, there are two parameters for the location algorithm: the topology of the network, and the members of the Gaggle. Given complete information about both, it would be easy to select the best member to invoke. But we do not have such information. Our response is twofold: first, we try to propagate as much information as we can, as cheaply as possible; second, we recognize that our information will never be complete, and strive do as well as possible with what we have.

Stable Storage.

The Hermes object-finding algorithm uses stable storage as a last resort. We can increase the robustness of Gaggles by using the name service to provide a form of stable storage for the gaggleManager.

Whenever a member is added to a group, it is possible to update the (global) name-service to record this addition. Alternatively, the updates could be batched. Now, if a node cannot find those members of a Gaggle that it knows about, it can ask the name server for a membership list and see if there are additional members. Since the name server is not up to date, it cannot be relied on to supply the names of all members; since it is a global service, it is relatively expensive, and should be used only as a last resort. However, since members are never removed from a Gaggle, the information received from the name service, while incomplete, will never be incorrect.

So stable storage is implemented a little differently for a Gaggle than for an ordinary object; but not inelegantly. Just as objects that exist in a single place store their state at some single storesite, plural objects that exist in many places store their state in a distributed storesite, a name service.

The addMember operation.

When a member is added to a Gaggle, it is not clear to whom that information should be propagated. The membership table on the node where the *addMember* invocation occurred should certainly be updated. In addition, a name server update might be made or queued, as mentioned above. Beyond this, various alternatives are possible.

Since the reason to propagate membership information is to reduce the message traffic necessary to implement an invocation, any propagation strategy that uses extra messages is suspect. However, piggybacking Gaggle membership information onto existing node to node communication is promising. For example, nearby machines could be notified of new Gaggle members when status and load information is exchanged. Or, the next time an invocation for the GaggleInvokee is seen by the adding node, the membership update could be returned.

6.2. The Emerald implementation of Gaggles

The code for the Emerald run-time library that implements Gaggles is given in Figure 1. The only necessary additions to the Emerald language are the system primitives that implement *addMember* and that allocate an object identifier for the GaggleInvokee. This object identifier is the only state in a gaggleManager. It is constant and assigned at object creation time, so the gaggleManager is immutable. When a reference to a gaggleManager is

```
const Gaggle ←
    immutable object Gaggle
        export function of [memberType : type ] → [result : gaggleType ]
            where gaggleType ←
                typeobject gaggleType
                    function getSignature [ ] → [Signature]
                    operation new [ ] → [gaggleManager]
                end gaggleType
            where gaggleManager ←
                typeobject gaggleManager
                    operation addMember [memberType ] → [ ]
                    function invokee [ ] → [memberType ]
                end gaggleManager
            result ←
                immutable object gaggleCons
                    export function getSignature [ ] → [s : Signature]
                        s ← gaggleManager
                    end getSignature
                    export operation new [ ] → [aGaggleManager : gaggleManager ]
                        aGaggleManager ←
                            immutable object manager
                                initially
                                    const theInvokee ← % A system primitive generating
                                                       % a new object identifier
                                end initially
                                export operation addMember [newMember : memberType ] → [ ]
                                    % A system primitive handling member addition
                                end addMember
                                export operation invokee [ ] → [gaggleInvokee : memberType ]
                                    gaggleInvokee ← theInvokee
                                end invokee
                            end manager
                    end new
                end GaggleCons
    end Gaggle
```

Figure 1: Emerald implementation of Gaggles

passed from one object to another, thereby giving another object the ability to manage the Gaggle, the gaggleManager is actually passed by value. Thus, if the gaggleManager is passed to several objects, one of the objects may break without crippling the Gaggle: the gaggleManager has been automatically replicated.

7. Current Status

The original implementation of Emerald generated highly efficient native code for a network of five microVAX[TM] II processors [11]. It has been ported to networks of SUN[TM] workstations. However, both the generation of native code and the history of the implementation have made the compiler for this version of the system hard to maintain.

To promote the use of Emerald as a teaching and research tool, Norman Hutchison created a portable version of the Emerald compiler (written in Emerald), and a portable run-time system (written in portable C). However, this version of the language was restricted to a single address space.

During the summer of 1992, the present authors started to add distribution to the portable version of Emerald. As this work progressed, we began to consider the extensions described here. We hope that Gaggles will be implemented as part of our ongoing work to complete the distributed portable implementation of Emerald.

We have not come to any definite conclusion about the relative merits of one Gaggle finding algorithm over another; only benchmarks run on real implementations can give definitively decide that question. However, we have highlighted some of the problems involved, presented some possible solutions, and examined many of the choices.

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