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**HPJava**: data parallel extensions to Java

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**Abstract**

We outline an extension of Java for programming with distributed arrays. The basic programming style is Single Program Multiple Data (SPMD), but parallel arrays are provided as new language primitives. Further extensions include three distributed control constructs, the most important being a data-parallel loop construct. Communications involving distributed arrays are handled through a standard library of collective operations. Because the underlying programming model is SPMD programming, direct calls to MPI or other communication packages are also allowed in an HPJava program.

**1 Introduction**

The idea that Java may enable new programming environments, combining attractive user interfaces with high performance computation, is gaining increasing attention amongst computational scientists. Java boasts a direct simplicity reminiscent of Fortran, but also incorporates many of the important ideas of modern object-oriented programming. Of course it comes with an established track-record in the domains of Web and Internet programming.

This article will focus specifically on the potential of Java as a language for scientific parallel programming. We envisage a framework called **HPJava**. This would be a general environment for parallel computation. Ultimately it should combine tools, class libraries, and language extensions to support various established paradigms for parallel computation, including shared memory programming, explicit message-passing, and array-parallel programming. Other paradigms (for example, Linda or coarse-grained data-flow) may come later, to-
gether with bindings to higher-level libraries and application-specific libraries such as CHAOS [7], ScalAPACK [1], Global Arrays [8] or DAGH [9].

This is a large vision, and the current article only discusses some first steps towards a general framework. In particular we will make specific proposals for the sector of HPJava most directly related to its namesake: High Performance Fortran. We will be concentrating on array-parallel programming.

For now we do not propose to import the full HPF programming model to Java. After several years of effort by various compiler groups, HPF compilers are still quite immature. It seems difficult justify a comparable effort for Java before success has been convincingly demonstrated in Fortran. In any case there are features of the HPF model that make it less attractive in the context of the integrated parallel programming environment we envisage. Although an HPF program can interoperate with modules written in other parallel programming styles through the HPF extrinsic procedure interface, that mechanism is quite awkward. Rather than follow the HPF model directly, we propose introducing some of the characteristic ideas of HPF—specifically its distributed array model and array intrinsic functions and libraries—into a basically SPMD programming model. Because the programming model is SPMD, direct calls to MPI [2] or other communication packages are allowed from the HPJava program.

The language outlined here provides HPF-like distributed arrays as language primitives, and new distributed control constructs to facilitate access to the local elements of these arrays. In the SPMD mold, the model allows processors the freedom to independently execute complex procedures on local elements: it is not limited by SIMD-style array syntax. All access to non-local array elements must go through library functions—typically collective communication operations. This puts an extra onus on the programmer; but making communication explicit encourages the programmer to write algorithms that exploit locality, and simplifies the task of the compiler writer. On the other hand, by providing distributed arrays as language primitives we are able to simplify error-prone tasks such as converting between local and global array subscripts and determining which processor holds a particular element. As in HPF, it is possible to write programs at a natural level of abstraction where the meaning is insensitive to the detailed mapping of elements. Lower-level styles of programming are also possible.

Our compiler will be implemented as a translator to ordinary Java with calls to a suitable run-time library. At the time of writing the underlying library is already available [5], and the Java interface needed by the translator is under development. The translator itself is being implemented in a compiler construction framework developed in the PCRC project [6, 12].
2 Multidimensional arrays

First we describe a modest extension to Java that adds a class of true multi-dimensional arrays to the standard Java language. The new arrays allow regular section subscripting, similar to Fortran 90 arrays. The syntax described in this section is a subset of the syntax introduced later for parallel arrays and algorithms: the only motivation for discussing the sequential subset first is to simplify the overall presentation. No attempt is made to integrate the new multidimensional arrays with the standard Java arrays: they are a new kind of entity that coexists in the language with ordinary Java arrays. There are good technical reasons for keeping the two kinds of array separate\(^1\).

The type-signatures and constructors of the multidimensional array use double brackets to distinguish them from ordinary arrays:

\[
\text{int } [[,]] \ a = \text{new int } [[5, 5]] ;
\]

\[
\text{float } [[,]] \ b = \text{new float } [[10, n, 20]] ;
\]

\[
\text{int } [\[]] \ c = \text{new int } [[100]] ;
\]

\[
a, b \text{ and } c \text{ are respectively 2-, 3- and one-dimensional arrays. Of course } c \text{ is very similar in structure to the standard array } d, \text{ created by}
\]

\[
\text{int } \[] \ d = \text{new int } [100] ;
\]

\[
c \text{ and } d \text{ are not identical, though}\(^2\).
\]

Access to individual elements of a multidimensional array goes through a subscripting operation involving single brackets, for example

\[
\text{for(int } i = 0 ; i < 4 ; i++)
\]
\[
a [i, i + 1] = i + c [i] ;
\]

For reasons that will become clearer in later sections, this style of subscripting is called \textit{local subscripting}. In the current sequential context, apart from the fact that a single pair of brackets may include several comma-separated subscripts, this kind of subscripting works just like ordinary Java array subscripting. Subscripts always start at zero, in the ordinary Java or C style (there is no Fortran-like lower bound).

In general our language has no idea of Fortran-like array assignments. In

\[
\text{int } [[,]] \ e = \text{new int } [[n, m]] ;
\]

\[
\ldots
\]
\[
a = e ;
\]

\(^1\)The run-time representation of our multi-dimensional arrays includes extra descriptor information that would simply encumber the large class “non-scientific” Java applications.

\(^2\)For example, \textit{c} allows section subscripting, whereas \textit{d} does not.
the assignment simply copies a handle to object referenced by e into a. There is no element-by-element copy involved. Similarly we introduce no idea of elemental arithmetic or elemental function application. If e and a are arrays, the expressions

\[
\text{Math.cos(e)}
\]

are type errors.

Our HPJava does import a Fortran-90-like idea of array regular sections. The syntax for section subscripting is different to the syntax for local subscripting. Double brackets are used. These brackets can include scalar subscripts or subscript triplets.

A section is an object in its own right—its type is that of a suitable multi-dimensional array. It describes some subset of the elements of the parent array. This is slightly different to the situation in Fortran, where sections cannot usually be captured as named entities\(^3\).

\[
\text{int} \ [2] e = \text{a} \ [2, 2] ;
\]

\[
\text{foo(b} \ [0, 10 : 2]) ;
\]

e becomes an alias for the 3rd row of elements of a. The procedure foo should expect a two-dimensional array as argument. It can read or write to the set of elements of b selected by the section. As in Fortran, upper or lower bounds can be omitted in triplets, defaulting to the actual bound of the parent array, and the stride entry of the triplet is optional. The subscripts of e, like any other array, start at 0, although the first element is identified with a \([2, 2]\).

In our language, unlike Fortran, it is not allowed to use vectors of integers as subscripts. The only sections recognized are regular sections defined through scalar and triplet subscripts.

The language provides a library of functions for manipulating its arrays, closely analogous to the array transformational intrinsic functions of Fortran 90:

\[
\text{int} \ [5, 5] f = \text{new int} \ [5, 5] ;
\]

\[
\text{HPJlib.shift(f, a, -1, 0, CYCL)} ;
\]

\[
\text{float} g = \text{HPJlib.sum(b)} ;
\]

\[
\text{int} \ [100] h = \text{new int} \ [100] ;
\]

\[
\text{HPJlib.copy(h, c)} ;
\]

The shift operation with shift-mode CYCL executes a cyclic shift on the data in its second argument, copying the result to its first argument—an array of the same shape. In the example the shift amount is -1, and the shift is performed

---

\(^3\)Unless a section appears as an actual argument to a procedure, in which case the dummy argument names that section, or it is the target of a pointer assignment.
in dimension 0 of the array—the first of its two dimensions. The sum operation simply adds all elements of its argument array. The copy operation copies the elements of its second argument to its first—it is something like an array assignment. These functions may have to be overloaded to apply to some finite set of array types, e.g., they may be defined for arrays with elements of any suitable Java primitive type, up to some maximum rank of array. Alternatively the type-hierarchy for arrays can be defined in a way that allows these functions to be more polymorphic.

3 Process arrays

HPJava adds class libraries and some additional syntax for dealing with distributed arrays. These arrays are viewed as coherent global entities, but their elements are divided across a set of cooperating processes. As a pre-requisite to introducing distributed arrays we discuss the process arrays over which their elements are scattered.

An abstract base class Proc has subclasses Proc1, Proc2, …, representing one-dimensional process arrays, two-dimensional process arrays, and so on.

Proc2 p = new Proc2(2, 2);
Proc1 q = new Proc1(4);

These declarations set \( p \) to represent a 2 by 2 process array and \( q \) to represent a 4-element, one-dimensional process array. In either case the object created describes a group of 4 processes. At the time the Proc constructors are executed the program should be executing on four or more processes. Either constructor selects four processes from this set and identifies them as members of the constructed group.

Proc has a member function called member, returning a boolean value. This is true if the local process is a member of the group, false otherwise.

if (p.member()) {
  ...
}

The code inside the if is executed only if the local process is a member \( p \). We will say that inside this construct the active process group is restricted to \( p \).

The multi-dimensional structure of a process array is reflected in its set of process dimensions. An object is associated with each dimension. These objects are accessed through the inquiry member dim.

\(^4\)There is no cooperation between the two constructor calls for \( p \) and \( q \), so an individual physical process might occur in both groups or in neither. As an option not illustrated here, vectors of ids can be passed to the Proc constructors to specify exactly which processes are included in a particular group.

5
Dimension x = p.dim(0);
Dimension y = p.dim(1);
Dimension z = q.dim(0);

The object returned by the dim inquiry has class Dimension. The members
of this class include the inquiry crd. This returns the coordinate of the local
process with respect to the process dimension. The result is only well-defined if
the local process is a member of the parent process array. The inner body code in

if(p.member())
  if(x.crd() == 0)
    if(y.crd() == 0) {
      ...
    }

will only execute on the first process from p, with coordinates (0,0).

4 Distributed arrays

Some or all of the dimensions of a multi-dimensional array can be declared
to be distributed ranges. In general a distributed range is represented by an
object of class Range. A Range object defines a range of integer subscripts,
and defines how they are mapped into a process array dimension. In fact the
Dimension class introduced in the previous section is a subclass of Range. In this
case the integer range is just the range of coordinate values associated with the
dimension. Each value in the range is mapped, of course, to the process (or slice
of processes) with that coordinate. This kind of range is also called a primitive
range. More complex subclasses of Range implement more elaborate maps from
integer ranges to process dimensions. Some of these will be introduced in later
sections. For now we concentrate on arrays constructed with Dimension objects
as their distributed ranges.

The syntax of section 2 is extended in the following way to support distributed arrays

- A distributed range object may appear in place of an integer extent in the
  “constructor” of the array (the expression following the new keyword).

- If a particular dimension of the array has a distributed range, the corre-
  sponding slot in the type signature of the array should include a # symbol.

- In general the constructor of the distributed array must be followed by an
  on clause, specifying the process group over which the array is distributed.
  Distributed ranges of the array must be distributed over distinct dimen-
  sions of this group.\(^5\)

\(^5\)The on clause can be omitted in some circumstances—see section 5.
Assume p, x and y are declared as in the previous section, then

```java
float [[#,#,]] a = new float [[x, y, 100]] on p;
```

defines a as a 2 by 2 by 100 array of floating point numbers. Because the
first two dimensions of the array are distributed ranges—dimensions of p—a is
actually realized as four segments of 100 elements, one in each of the processes
of p. The process in p with coordinates i, j holds the section a [[i, j, :]].
The distributed array a is equivalent in terms of storage to four local arrays
defined by

```java
float [] b = new float [100];
```

But because a is declared as a collective object we can apply collective opera-
tions to it. The HPJlib functions introduced in section 2 apply equally well to
distributed arrays, but now they imply inter-processor communication.

```java
float [[#,#,]] a = new float [[x, y, 100]] on p,
    b = new float [[x, y, 100]] on p;

HPJlib.shift(a, b, -1, 0, CYCL);
```

The shift operation causes the local values of a to be overwritten with values
of b from a processor adjacent in the x dimension.

There is a catch in this. When subscripting the distributed dimensions of an
array it is simply disallowed to use subscripts that refer to off-processor elements.
While this:

```java
int i = x.crd(), j = y.crd();

a[i, j, 20] = a[i, j, 21];
```
is allowed, this:

```java
int i = x.crd(), j = y.crd();

a[i, j, 20] = b[(i + 1) % 2, j, 20];
```
is forbidden. The second example could apparently be implemented using a
nearest neighbour communication, quite similar to the shift example above.
But our language imposes an strict policy distinguishing it from most data paral-
lel languages: while library functions may introduce communications, language
primitives such as array subscripting never imply communication.

If subscripting distributed dimensions is so restricted, why are the i, j sub-
scripts on the arrays needed at all? In the examples of this section these sub-
scripts are only allowed one value on each processor. Well, the inconvenience
of specifying the subscripts will be reduced by language constructs introduced
later, and the fact that only one subscript value is local is a special feature of
the primitive ranges used here. The higher level distributed ranges introduced
later map multiple elements to individual processes. Subscripting will no longer
look so redundant.
5 The on construct and the active process group

In the section 3 the idiom

```java
if(p.member()) {
    ...
}
```

appeared. Our language provides a short way of writing this construct

```java
on(p) {
    ...
}
```

In fact the on construct provides some extra value. Informally we said in section 3 that the active process group is restricted to p inside the body of the p.member() conditional construct. The language incorporates a more formal idea of an active process group (APG). At any point of execution some process group is singled out as the APG. An on(p) construct specifically changes the value of the APG to p. On exit from the construct, the APG is restored to its value on entry.

Elevating the active process group to a part of the language allows some simplifications. For example, it provides a natural default for the on clause in array constructors. More importantly, formally defining the active process group simplifies the statement of various rules about what operations are legal inside distributed control constructs like on.

6 Higher-level ranges and locations

The class BlockRange is a subclass of Range which describes a simple block-distributed range of subscripts. Like BLOCK distribution format in HPF, it maps blocks of contiguous subscripts to each element of its target process dimension\(^6\). The constructor of BlockRange usually takes two arguments: the extent of the range and a Dimension object defining the process dimension over which the new range is distributed.

```java
Procs2 p = new Procs2(3, 2);

Range x = new BlockRange(100, p.dim(0));
Range y = new BlockRange(200, p.dim(1));

float [[#, #]] a = new float [[x, y]] on p;
```

a is created as a 100 × 200 array, block-distributed over the 6 processes in p. The fragment is essentially equivalent to the HPF declarations

\(^6\)Other higher-level ranges include CyclicRange, which produces the equivalent of CYCLIC distribution format in HPF.
\begin{figure}
\centering
\begin{tabular}{cccccc}
\hline
& & & & & \\
0 & 1 & 2 & 3 & \ldots & N-1 \\
\end{tabular}
\caption{A range regarded as a set of locations, or slots.}
\end{figure}

\texttt{!HPFS \texttt{PROCESSORS} p(3, 2)}

\texttt{REAL} a(100, 200)

\texttt{!HPFS \texttt{DISTRIBUTE} a(BLOCK, BLOCK) \texttt{ONTO} p}

Subscribing distributed arrays with non-primitive ranges introduces some new problems. An array access such as

\begin{verbatim}
a [17, 23] = 13 ;
\end{verbatim}

is perfectly legal if the local process holds the element in question. But determining whether an element is local is no longer so easy. When arrays had only primitive distributed ranges, it was straightforward to check that accesses were local—the subscript simply had to be equal to the local coordinate. With higher-level ranges, that simple condition no longer holds.

In practise it is unusual to use integer values directly as local subscripts in distributed array dimensions. Instead the idea of a \texttt{location} is introduced. A location can be viewed as an abstract element, or “slot”, of a distributed range. Conversely, a range can be thought of as a set of locations. This model of a range is visualized in figure 1. An individual location is described by an object of the class \texttt{Location}. Each \texttt{Location} element is mapped to a particular slice of a process grid. In general two locations are identical only if they come from the same position in the same range. A scripting syntax is used to represent location \texttt{n} in range \texttt{x}:

\begin{verbatim}
Location i = x [n]
\end{verbatim}

This is an important idea in HPJava. By working in terms of abstract locations—elements of distributed ranges—one can usually respect locality of reference without resorting explicitly to low-level local subscripts and process ids. In fact the location can be viewed as an abstract data type incorporating these lower-level offsets.

Publically accessible fields of \texttt{Location} include \texttt{dim} and \texttt{crd}. The first is the process dimension of the parent range. The second is coordinate in that dimension to which the element is mapped. So the access to element \texttt{a [17, 23]} could now be guarded by conditionals as follows:

\begin{verbatim}
Location i = x [17], j = y [23] ;
if(i.crd == i.dim.crd())
\end{verbatim}
if(j.crd == j.dim.crd())
a [17, 23] = 13 ;

This is still quite verbose and error-prone. The language provides a second distributed control construct (analogous to on) to deal with this common situation. The new construct is called at, and takes a location as its argument. The fragment above can be replaced with:

Location i = x [17], j = y [23] ;

at(i)
at(j)
a [17, 23] = 13 ;

This is more concise, but still involves some redundancy because the subscripts 17 and 23 appear twice. A natural extension is to allow locations to be used directly as array subscripts:

Location i = x [17], j = y [23] ;

at(i)
at(j)
a [i, j] = 13 ;

Locations used as array subscripts must be elements of the corresponding ranges of the array.

The range class has a member function

int Range.idx(Location i)

which can be used to recover the integer subscript, given a location in the range.

There is a restriction that an at(i) construct should only appear at a point of execution where i.dim is a dimension of the active process group. In the examples of this section this means that an at(i) construct, say, should normally be nested directly or indirectly inside an on(p) construct.

7 Distributed loops

Good parallel algorithms don’t usually expend many lines of code assigning to isolated elements of distributed arrays. The at mechanism of the previous section is often useful, but a more pressing need is a mechanism for parallel access to distributed array elements. The last and most important distributed control construct in the language is called over. It implements a distributed parallel loop. Conceptually it is quite similar to the FORALL construct of Fortran, except that the over construct specifies exactly where its parallel iterations are to be performed. The argument of over is a member of the special class Index. The class Index is a subclass of Location, so it is syntactically correct to use an index as an array subscript.7 Here is an example of a pair of nested over loops:

7But the effect of such subscripting is only well-defined inside an over construct parametrised by the index in question.
float [[#,#]] a = new float [[x, y]],
    b = new float [[x, y]];
...
Index i, j;
over(i = x | :)
    over(j = y | :)
        a [i, j] = 2 * b [i, j];

The body of an `over` construct executes, conceptually in parallel, for every
location in the range of its index (or some subrange if a non-trivial triplet is
specified). An individual “iteration” executes on just those processors holding
the location associated with the iteration. In a particular iteration, the location
component of the index (the base class object) is equal to that location. The net
effect of the example above should be reasonably clear. It assigns twice the value
of each element of `b` to the corresponding element of `a`. Because of the rules
about where an individual iteration iterates, the body of an `over` can usually only
combine elements of arrays that have some simple alignment relation relative to
one another. The `idx` member of range can be used in parallel updates to give
expressions that depend on global index values.

With the `over` construct we can give some useful examples of parallel pro-
grams. Figure 2 is the famous Jacobi iteration for a two dimensionsal
Laplace equation. We have used cyclic `shift` to implement nearest neighbour
communications.

Copying whole arrays into temporaries is not an efficient way of accessing
nearest neighbours in an array. Because this is such a common pattern of
communication, the standard library supports `ghost regions`. Distributed arrays
can be created in such a way that the segment stored locally is extended with
some halo. This halo caches values stored in the segments of adjacent processes.
The cached values are explicitly brought up to date by the library operation
`writeHalo`.

An optimized version of the Jacobi program is give in figure 3. This version
only involves a singe array temporary. A new constructor for `BlockRange` is
provided. This allows the width of the ghost extensions to be speicified. The
arguments of `writeHalo` itself are an array with suitable extensions and two vec-
tors. The first defines in each dimension the width of the halo that must actually
be updated, and the second defines the treatment at the ends of the range—in
this case the ghost edges are updated with cyclic wraparound. The new con-
structor and new `writeHalo` function are simply standard library extensions.
One new piece of syntax is needed: the addition and subtraction operators are

8Formally `|` is being used here as an operator that combines a range and a triplet to return
an object of the iterator class `Index`.

9Laplace's equation with cyclic boundary conditions is not particularly useful, but it illus-
trates the language features. More interesting boundary conditions can easily be incorporated
later. Incidentally, this is a suitable place to mention that the array arguments of `shift` must be
`aligned` arrays—they must have identical distributed ranges.
Proc2 p = new Proc2(2, 2);

on(p) {
    Range x = new BlockRange(100, p.dim(0));
    Range y = new BlockRange(200, p.dim(1));
    float [[#,#]] u = new float [[x, y]]; // ... some code to initialise 'u'
    float [[#,#]] unx = new float [[x, y]], upx = new float [[x, y]],
        uny = new float [[x, y]], upy = new float [[x, y]]; 
    HPJlib.shift(unx, u, 1, 0, CYCL);
    HPJlib.shift(upx, u, -1, 0, CYCL);
    HPJlib.shift(undy, u, 1, 1, CYCL);
    HPJlib.shift(upy, u, -1, 1, CYCL);
    Index i, j;
    over(i = x | :)
        over(j = y | :)
            u[i, j] = 0.25 * (unx[i, j] + upx[i, j] +
                              uny[i, j] + upy[i, j]);
}

Figure 2: Jacobi iteration using shift.
Proc2 p(2, 2) ;

on(p) {
  Range x = new BlockRange(100, p.dim(0), 1); // ghost width 1
  Range y = new BlockRange(200, p.dim(1), 1); // ghost width 1
  float [[#,#]] u = new float [[x, y]] ;

  // ... some code to initialise 'u'

  int [] widths = {1, 1};          // Widths actually updated
  Mode [] modes = {CYCL, CYCL};    // Wraparound at ends.

  HPJlib.writeHalo(u, widths, modes);
  float [[#,#]] v = new float [[x, y]] ;

  Index i, j;
  over(i = x | :)
    over(j = y | :)
      v [i, j] = 0.25 * (u [i + 1, j] + u [i - 1, j] +
                      u [i, j + 1] + u [i, j + 1]) ;

  HPJlib.copy(u, v) ;
}

Figure 3: Jacobi iteration using writeHalo.

overloaded so that integer offsets can be added or subtracted to Location objects, yielding new, shifted, locations. The usual access rules apply—this kind of shifted access is illegal if it implies access to off-processor data. It only works if the subscripted array has suitable ghost extensions.

8 Other features

We have already described most of the important language features we propose to implement. Two additional features that are quite important in practice but have not been discussed are subranges and subgroups. A subrange is simply a range which is a regular section of some other range, created by syntax like x [0 : 49]. Subranges are created tacitly when a distributed array is subscripted with a triplet, and they can also be used directly to create distributed arrays with general HPF-like alignments. A subgroup is some slice of a process array, formed by restricting process coordinates in one or more dimensions to
single values. Again they may be created implicitly by section subscripting, this time using a scalar subscript. They also formally describe the state of the active process group inside at and over constructs.

The framework described is much more powerful than space allows us to demonstrate in this paper. This power comes in part from the flexibility to add features by extending the libraries associated with the language. We have only illustrated the simplest kinds of distribution format. But any HPF 1.0 array distribution format, plus various others, can be incorporated by extending the Range hierarchy in the run-time library. We have only illustrated shift and writer Halo operations from the communication library, but the library also includes much more powerful operations for remapping arrays and performing irregular data accesses. Our intention is to provide minimal language support for distributed arrays, just enough to facilitate further extension through construction of new libraries.

For a more complete description of a slightly earlier version of the proposed language, see [4].

9 Discussion and related work

We have described a conservative set of extensions to Java. In the context of an explicitly SPMD programming environment with a good communication library, we claim these extensions provide much of the concise expressiveness of HPF, without relying on very sophisticated compiler analysis. The object-oriented features of Java are exploited to give an elegant parameterization of the distributed arrays of the extended language. Because of the relatively low-level programming model, interfacing to other parallel-programming paradigms is more natural than in HPF. With suitable care, it is possible to make direct calls to, say, MPI from within the data parallel program. In [3] we suggest a concrete Java binding for MPI.

We will mention two related projects. Spar [11] is a Java-based language for array-parallel programming. Like our language it introduces multi-dimensional arrays, array sections, and a parallel loop. There are some similarities in syntax, but semantically Spar is very different to our language. Spar expresses parallelism but not explicit data placement or communication—it is a higher level language. ZPL [10] is a new programming language for scientific computations. Like Spar, it is an array language. It has an idea of performing computations over a region, or set of indices. Within a compound statement prefixed by a region specifier, aligned elements of arrays distributed over the same region can be accessed. This idea has certain similarities to our over construct. Communication is more explicit than Spar, but not as explicit as in the language discussed in this article.
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