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ViC*: A Preprocessor for Virtual-Memory C*

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Abstract

This paper describes the functionality of ViC*, a compiler-like preprocessor for out-of-core C*. The input to ViC* is a C* program but with certain shapes declared outofcore, which means that all parallel variables of these shapes reside on disk. The output is a standard C* program with the appropriate I/O and library calls added for efficient access to out-of-core parallel variables.

1 Introduction

Although parallel computers were originally designed with processing speed in mind, they have proven equally valuable for their ability to solve problems with very large data requirements. Indeed, parallel computers have opened up a new range of possibilities for scientific computing. Perhaps the best known examples are “Grand Challenge” problems such as those from environmental modeling, coupled field computations, and computational fluid dynamics.

As the capacity of parallel computers has increased, however, so have the appetites of users. Throughout the history of electronic computing, no matter how big and fast the top machines have been, there have always been applications that needed them to be bigger and faster, and it remains true today.

Over thirty years ago, computer architects devised virtual memory to solve this problem for sequential machines [Den70]. We see two approaches in today’s parallel machines:

• Have no built-in support for virtual memory. Without built-in virtual-memory support, applications whose memory requirements exceed the available memory typically keep their data on a disk system and perform explicit disk accesses. The explicit I/O calls consequently add to the programmer’s task, thus increasing the time spent in software development. The programmer spends time that could otherwise be spent on application-specific code instead worrying about disk I/O. Moreover, because I/O is often tricky to program, correct code is more difficult to develop and maintain.

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• Run traditional sequential virtual memory on the individual nodes, which requires a MIMD architecture. This approach frees the programmer from coding explicit I/O calls, but because it fails to take advantage of aggregate data-parallel operations, it also yields suboptimal performance. There have been significant technical advances recently on how to carefully plan disk accesses for common data-parallel operations and algorithms [CGG*94, Cor92, Cor93, CSW94, GTVV93, Kof94, NV91, NV92, VS94, WGR93]. The performance improvements gained by using these methods can be tremendous, and their impacts increase with the problem size. They require a degree of coordination among the processors and disks that unrelated virtual-memory systems on separate nodes cannot provide.

Built-in virtual-memory support for data-parallel programming would allow the memory requirements of application programs to exceed the available memory size without increasing software development time or software complexity. Yet, programmers would not need specialized knowledge of I/O-optimal algorithms in order to avoid huge performance penalties.

This paper describes a linguistic step toward such a solution. Our approach is based on the data-parallel language C* [TMC93]. A preprocessor, ViC* (Virtual-memory C*), transforms a C* program with parallel variables so large that they must reside on disk into a C* program with all parallel variables fitting in memory and explicit I/O and library calls added. A ViC* source program does not declare individual variables as disk-resident, or out-of-core; instead, any C* shape may be declared to be outofcore, which means that all parallel variables of this shape are out-of-core. Linguistically, the only difference between a ViC* program and a "standard" C* program is the outofcore shape modifier. The explicit I/O calls added by ViC* are direct parallel disk reads and writes of sections of out-of-core parallel variables. The library calls added by ViC* are typically for operations requiring communication in out-of-core parallel variables, e.g., reductions, gets, and sends.

One principle of this project is to exploit existing languages and software as much as possible. Although it performs as much analysis as many compilers, ViC* is a preprocessor. A programmer using ViC* would first run the source program (say prog.vic), which contains outofcore shape declarations, through ViC*, which produces a standard C* program (say prog.cs). This C* program would then be run through the usual C* compiler and linked with special ViC* libraries (containing the out-of-core communication functions) using the compiler flag -l vic to produce an executable file.

Why choose C* as a base language? We want a data-parallel language that is used at several sites, for which there is existing code, and that is not High-Performance Fortran (HPF). We are interested in data-parallelism because it has proven to be a valuable parallel-programming paradigm and because recent I/O-optimal algorithms fit nicely into it. We want a language in use at several sites and for which there is existing code because we hope that scientific programmers and others will really use ViC*. And we wish to sidestep HPF because there are already two out-of-core HPF projects that we know of, at Syracuse University [BTC94, TBC94] and Rice University [KKP94], and because C* presents different implementation challenges from HPF. In particular, HPF uses arrays for parallelism and C* uses shapes, HPF has a much more restricted notion of context than C*, and HPF's style of data distribution differs from that of C*. Moreover, the ViC* run-time library may be substantially different from those in the out-of-core HPF projects. Despite recent setbacks at Thinking Machines Corporation, where C* was developed, we believe that C*—or at least the concepts behind it—will persist for some time to come.

The remainder of this paper is organized as follows. Section 2 presents a brief overview of the C* language and the ViC* extensions. The ViC* data structures and run-time interface reside in a header file, which Section 3 describes. Section 4 shows how ViC* modifies out-of-core shape and
data declarations. Sections 5 and 6 briefly discuss how ViC* transforms out-of-core with and where statements. Most of ViC*'s processing deals with expressions and optimizations, which Section 7 covers. Section 8 touches on issues relating to function calls with out-of-core parameters or return values. Section 9 offers some concluding remarks. Finally, Appendix A shows the C* code generated by a sample program.

2 Background concepts and overview of ViC*

This section introduces the parallel programming model and the language features of C* and ViC* that implement it. More information about the C* language appears in [TMC93].

C*, and hence ViC*, support data-parallel programming, in which a sequential program operates on parallel arrays of data, with each virtual processor operating on one parallel data element. The underlying computer multiplexes a set of physical processors among the virtual processors to support the parallel model. Scalar data remains global to all virtual processors.

Each parallel variable in C* has a shape, which describes its rectangular structure. A shape defines the logical configuration of parallel data in virtual processors. At any point in the program, a current shape is in force. Most parallel operations must operate on data of the current shape. A with statement selects the current shape, referred to by the reserved word current.

All C* operations are controlled by a context, which describes the active positions in parallel variables of the current shape. Active positions are those whose virtual processors initiate parallel operations. When a shape is made the current shape, all of its positions are active. The where statement narrows the context by selecting a subset of the active positions within the shape. An optional else clause of a where statement selects the complementary subset. The everywhere statement makes all positions active. Context has both static and dynamic qualities. It is static because completion of a where or everywhere statement restores the previous context. It is dynamic because it is implicitly passed to any called function.

Parallel communication transfers parallel data among the virtual processors. There are several forms of parallel communication. Reductions combine elements of a parallel variable into a scalar result. Left indexing a parallel variable stores or extracts a scalar in a single virtual processor. Parallel left indexing addresses data in a set of virtual processors. Virtual processors executing a get operation in an expression fetch data from other virtual processors. Virtual processors executing a send operation in an assignment transmit data to other virtual processors. Some readers may be more familiar with get as "gather" and with send as "scatter." The standard C* library includes specialized get and send operations for grid topologies as well as other forms of communication, notably scans.

C* is restricted to in-core data stored in the computer's main memory. ViC* processes large out-of-core parallel data sets stored on disk. ViC* extends the C* shape declaration statement by allowing the outofcore storage-class modifier on shape declarations. The outofcore modifier indicates that parallel variables of the shape in question normally reside outside the main memory. (Typically, outofcore variables will reside on a parallel disk system.) ViC* uses this information to access parallel variables of an outofcore shape. The keyword outofcore is a reserved word in our implementation. Currently, ViC* needs to know at compile time whether each shape (even those referenced by pointer) is outofcore. Eventually, we would like to be able to do without such a modifier and let ViC* determine which shapes should be out-of-core based on their size, the size of the main memory, and other related factors.

To translate out-of-core operations, ViC* decomposes a program into basic blocks. A basic block [ASU86] is a maximal sequence of statements with linear control flow. Types of statements
within a basic block are declarations, assignments, expressions, subroutine calls, as well as with and where statements. (Although where resembles a parallel if, it affects execution within virtual processors rather than control flow.) A directed acyclic graph (dag) represents data dependencies in a basic block. Basic blocks are further divided into simple blocks. A simple block is a subset of a basic block delimited by subroutine calls or communication within out-of-core shapes. Each simple block results in a sectioning loop in the C* program produced by ViC*. A simple block strip-mines [ZC90] out-of-core data by iterating over in-core sections or strips of the data.

To improve performance, ViC* uses dataflow analysis to determine which out-of-core data is required from each simple block in subsequent execution. Such data is live. A variable for which there are no further references is dead. Variables are always dead at the end of the block in which they are declared.

Sample program

We illustrate some of the above concepts with the ViC* program in Figure 1. The program declares an out-of-core shape series. Parallel variables of this shape are vectors of 2^{40} elements. The out-of-core parallel variable normal is a vector of 2^{40} floats. Within the function example, we declare out-of-core parallel variables harmonic and k in this shape. The variable k is initialized with the pcoord intrinsic function, which returns the index of each position along an axis of a shape. For i = 0, 1, ..., N - 1 the ith position of k (denoted [i]k in C*) has the value i. The where statement narrows the context to the positive positions. The first statement in the where body assigns elements of harmonic the reciprocals of k, so that [i]harmonic equals 1/i, for i = 1, 2, ..., N - 1. Narrowing the context to positive positions avoids a division by 0. A sum reduction, denoted by the += operator, sums all elements of harmonic into sum. The series is normalized by the reciprocal of this sum into normal. Finally, a send operation shifts the elements of normal, sending each element to the previous position. Within the parallel left-index expression, the period denotes the index vector; hence this statement executes in parallel the assignments

```
[0]normal = [1]normal;
...
[N-2]normal = [N-1]normal;
```

3  Header File

The preprocessor includes a standard header file with every compilation. Figure 2 shows this file, which defines ViC* data structures and declares runtime support routines for memory-management and I/O. ViC* uses names beginning ViC_ to avoid conflicts with the source program.

ViC* transforms out-of-core shape and data declarations into ViC_shape and ViC_data declarations. A ViC_shape structure describes an out-of-core shape. The positions, rank, and dimensions fields describe a parallel data configuration similar to an in-core shape, but without in-core size limitations. A shape also has a current context, represented here by a pointer to parallel boolean variable. A ViC_data structure describes a single out-of-core variable. It records the variable shape and identifies either a file with out-of-core data or a scalar initial value for a file yet to be created.

C* defines the current shape and context as global state, which is automatically passed to subroutines. ViC* implements these with global pointers to the current out-of-core shape and context. It transforms out-of-core with and where statements into operations on these pointers.
/* compute a truncated harmonic series and normalize it */

#define N (1L<<40) /* N = 2**40 */

tdefoutofcore shape [N]series; /* series of terms */
float:series normal; /* normalized terms */

void example()
{
    float:series harmonic; /* truncated harmonic series */
    float sum; /* series summation */
    int:series k;

    with (series) {
        k = pcoord(0); /* index array */
        where (k > 0) {
            harmonic = 1.0 / k; /* 1/k (0 < k < N) */
            sum += harmonic; /* sum terms */
            normal = harmonic * (1.0 / sum); /* normalized terms */
            [-1]normal = normal; /* shift series */
        }
    }
}

Figure 1: A sample ViC* program.

Other ViC* runtime support subroutines (ViC__Open through ViC__Copy in Figure 2) allocate in-core strips of out-of-core data and transfer these strips to and from data files. The routines determine the in-core shape at runtime to make the best use of available memory.

ViC* converts out-of-core operations into loops that iterate over in-core sections from disk files. Several macros (ViC__DCL through ViC__CLOSE in Figure 2) simplify declarations and file access. These macros use the standard preprocessor token-concatenation operator ## to reference auxiliary variables. Variables of the form ViC__name_file and ViC__name_strip reference open file descriptors and in-core data. ViC* also introduces temporary variables beginning ViC__number to hold stacked context information and intermediate results.

Other library functions implement out-of-core parallel communication, with versions for a number of special cases [Cor92].

4 Processing of declarations

This section describes how ViC* processes out-of-core shape and data declarations. ViC* identifies out-of-core shape declarations by the outofcore modifier and replaces them with ViC__shape declarations. It scans variable declarations for these shapes to identify out-of-core data and replaces them with ViC__data declarations. ViC* detaches any out-of-core initializations for separate processing as assignments, and it copies other declarations unchanged to the output. Figure 3 shows several typical declarations, with the corresponding ViC*-generated output.

The out-of-core shape series has N positions in a 1-dimensional array. Its initial context is the parallel boolean variable ViC__everywhere. The declarations of out-of-core variables a, aa, and ap are changed into declarations using ViC__data structures with shape series. The array aa is initialized with an array of ViC__data structures. These out-of-core variables have no initial value.

The data for an out-of-core variable is kept in a file identified by the ViC__data structure's...
```c
#define ViC_MAX_DIM 8

/* ViC out of core descriptors */
struct ViC_shape {  /* out of core shape */
  struct ViC_data *context;  /* pointer to the saved context */
  size_t positions;  /* the number of shape positions */
  int rank;  /* shape rank */
  size_t dimensions[ViC_MAX_DIM];  /* number of elements in each dimension */
};
typedef struct ViC_shape ViC_shape;

struct ViC_data {  /* out of core dataset */
  ViC_shape *datshape;  /* pointer to the variable shape */
  long fileid;  /* data file ID */
  void *initial;  /* or static initial value */
};
typedef struct ViC_data ViC_data;

/* ViC global "registers" passed implicitly to subroutines */
ViC_shape *ViC_current;  /* current shape */
ViC_data *ViC_context;  /* current context */

/* simple block processing */
shape *ViC_Stripshape(size_t sizes);  /* determine strip size & create shape */
void *ViC_Free(shape *s);  /* release shape for strip */
void void *ViC_Alloc(size_t size);  /* allocate in-core strip */
void *ViC_Free(void);  /* free in-core strips */

/* out-of-core I/O */
typedef struct ViC_file ViC_file;  /* data file descriptor */

ViC_file *ViC_Open(ViC_data *data);  /* open dataset */
void ViC_Close(ViC_file *file, ViC_data *data);  /* close dataset */
void ViC_Readstrip(void: void *data, size_t size, ViC_file *file);
void ViC_Writestrip(void: void *data, size_t size, ViC_file *file);
void ViC_Remove(ViC_data *data);  /* delete file out of scope */
void ViC_Copy(ViC_data *dst, ViC_data *src);  /* copy variables */

/* constants */
extern ViC_data ViC_everywhere;  /* everywhere context */

/* macros to declare/read/write strip data */
#define ViC_DCL(T, V, D)  
  T:current *ViC_##V##strip = ViC_Alloc(sizeof(ViC_##V##strip));  
  ViC_file *ViC_##V##file = ViC_Open(D)
#define ViC_LOOP  
  long ViC_position;
  for (ViC_position = 0;  
    ViC_position < ViC_current->positions;  
    ViC_position += positionsof(*ViC__stripshape))
#define ViC_READ(V)  
  ViC_Readstrip(ViC_##V##strip, sizeof(ViC_##V##strip), ViC_##V##file)
#define ViC_WRITE(V)  
  ViC_Writestrip(ViC_##V##strip, sizeof(ViC_##V##strip), ViC_##V##file)
#define ViC_CLOSE(V, D)  
  ViC_Close(ViC_##V##file, D)

Figure 2: The ViC.h file.
```
Figure 3: Some sample ViC* declarations and the corresponding output.
than the ViC* strategy.

5 Processing of with statements

This section outlines how ViC* processes with statements. A with statement establishes the current shape and sets the context to the current context for that shape. C* allows with statements to be nested, with the shape and context restored to their previous values after the end of the statement.

ViC* transforms a with statement that establishes an out-of-core shape into assignments to ViC_.current and ViC_.context. A temporary variable saves the previous shape and restores it after the with statement. ViC* defers output of a with statement until it encounters an out-of-core operation in the body of the with. The function ViC_.Stripshape computes an in-core shape used to hold in-core strips of the data.

Figure 4 shows the structure of the code generated for an out-of-core with statement of the form

```c
with (SHAPE) WITHBODY;
```

Here a local temporary variable, ViC_.prev, stacks the previous out-of-core shape. The statement body, WITHBODY, undergoes further processing.

6 Processing of where statements

This section describes how ViC* processes where statements. The where statement restricts the execution context for a statement. The everywhere variant of this statement widens the context to include all positions. This execution context determines which positions initiate parallel operations. Context is implicit in all parallel operations, including those in function calls. This use of a current context is one of the distinguishing features of C*, in contrast to FORTRAN 90 [ANS92, MR90], where context has static scope and may be applied only to parallel operations.

Like the with statement, a where statement saves state and restores it. ViC* replaces out-of-core where statements with operations on out-of-core boolean variables and the current context pointer, ViC_.context. It copies the current context, evaluates the where expression in the surrounding context, then computes the restricted context. For the else clause, the value of the where expression is complemented to narrow the context.

Figures 5 and 6 show the structure of the code generated for out-of-core where statements.
Figure 5: The ViC* code for the statement `where (CONTEXT) WHEREBODY; else ELSEBODY`. Lines beginning with @ undergo further processing by ViC*.

```c
{
    bool:outofcore current *ViC__:prev, /* saved context pointer */
    ViC__:new, /* new context data */
    ViC__:where; /* where expression */
    ViC__:prev = ViC__:context; /* save pointer to old */
    ViC__:where = CONTEXT; /* evaluate where expression */
    everywhere
    ViC__:new = *ViC__:prev & ViC__:where; /* copy old context data */
    ViC__:context = &ViC__:new; /* make current */
    WHEREBODY; /* execute body of where */
    everywhere
    ViC__:new = *ViC__:prev & !ViC__:where; /* recopy old context */
    ELSEBODY; /* execute body of where else */
    ViC__:context = ViC__:prev; /* restore previous context */
}
```

Figure 6: The ViC* code for the statement `everywhere EVERYBODY`. Lines beginning with @ undergo further processing by ViC*.

```c
{
    bool:outofcore current *ViC__:prev; /* saved context pointer */
    ViC__:prev = ViC__:context; /* save pointer to old */
    ViC__:context = &ViC__:everywhere; /* expand context */
    EVERYBODY; /* body of everywhere */
    ViC__:context = ViC__:prev; /* restore previous context */
}
```

where (CONTEXT)
    WHEREBODY;
else
    ELSEBODY;
and
everywhere EVERYBODY;
in terms of ViC* rather than C* code. ViC* does further processing on the context assignments and the statements in WHEREBODY, ELSEBODY, and EVERYBODY. The assignments to context variables are structured so that they may be combined with other out-of-core operations in the statement body. The scope of these variables is limited to the where statement, so that they need not be written to disk if the statement fits in a simple block. Some of the variables can be eliminated if there is no else part or for everywhere statements. Section 7 describes these and other optimizations.
7 Processing of expressions

This section describes how ViC* processes expressions, including C* assignments. Because ViC* is a front end to a C* compiler, it is only concerned with translating the outofcore extensions to C*. Out-of-core operations consist of parallel operations, reductions, and left indexing of outofcore variables. The outofcore syntax extensions ensure that all such operations can be identified in the source. Scalar C expressions and expressions involving in-core parallel variables are compiled by the C* compiler, and so they need no additional processing.

ViC* uses the current out-of-core shape and context to generate C* code that evaluates out-of-core expressions by making passes in sectioning loops. Each sectioning loop evaluates a series of in-core sections, or strips. The loop prologue evaluates any scalar expressions used in the body of the loop.

The loop body transfers data between out-of-core data files and the in-core strips and evaluates out-of-core expressions in the appropriate context. A loop may cover several contexts, that is, several where or everywhere statements.

Elementwise expressions

Let us first examine a simple elementwise expression:

```
harmonic = 1.0 / k;
```

becomes

```
{  
  shape *ViC__stripshape = ViC__Stripshape( /* determine strip shape */
      boolsizeof(bool:current) +
      boolsizeof(float:current) +
      boolsizeof(int:current));

  with (*ViC__stripshape) { /* in-core shape */
    ViC__DCL(bool, 30, ViC__context); /* in-core context */
    ViC__DCL(float, harmonic, &harmonic); /* in-core data */
    ViC__DCL(int, k, &k);

    ViC__LOOP {
      ViC__READ(30); /* in-core context */
      ViC__READ(k); /* in-core data */
      where (*ViC__30__strip) { /* establish context */
        *ViC__harmonic__strip = 1.0 / *ViC__k__strip; /* evaluate expression */
      }
      ViC__WRITE(harmonic); /* write output data */
    }

    ViC__Free(); /* free in-core strips */
    ViC__CLOSE(k, &k); /* close data files */
    ViC__CLOSE(harmonic, &harmonic);
    ViC__CLOSE(30, ViC__context);
  }

  ViC__FreeShape(ViC__stripshape); /* delete shape */
}
```

The function ViC__Stripshape computes and allocates the in-core shapes, given the sizes of the strip data and the context. The ViC__DCL macro declares and allocates the in-core data and then opens the data files. The ViC__READ macro reads data and context for the out-of-core expression,
with results written by ViC_WRITE. Once the loop completes, the files are closed and the shape and data are deallocated.

Reductions

A reduction operator, such as \(+=\), accumulates its result in a scalar variable. This reduction value is available at the end of the loop. The loop for

\[
\text{sum} = += \text{harmonic};
\]

with float scalar \text{sum} becomes

\[
\{
\text{shape} *\text{ViC\_stripshape} = \text{ViC\_Stripshape}, /* determine strip shape */
\text{boolsizeof(bool: current)} + 
\text{boolsizeof(float: current)};
\}
\]

with (\*\text{ViC\_stripshape}) {

\text{float} \text{ViC\_40} = 0.0; /* scalar temporary */
\text{ViC\_DCL(bool, 30, \text{ViC\_context}); /* in-core context */}
\text{ViC\_DCL(float, harmonic, &harmonic); /* in-core data */}
\}

\text{ViC\_LOOP} {
\text{ViC\_READ}(30); /* in-core context */
\text{ViC\_READ(harmonic); /* in-core data */}
\text{where} (\*\text{ViC\_30\_strip}) {

\text{ViC\_40} += \*\text{ViC\_harmonic\_strip}; /* evaluate reduction */
\}
\}

\text{ViC\_Free(); /* free in-core strips */}
\text{ViC\_CLOSE(harmonic, &harmonic); /* close data files */}
\text{ViC\_CLOSE(30, \text{ViC\_context});}
\}

\text{ViC\_Freeshape(\text{ViC\_stripshape}); /* delete shape */}
\}

\text{sum} = \text{ViC\_40}; /* result of reduction */

Optimization by loop fusion

ViC* attempts to reduce the amount of I/O by combining sectioning loops that share inputs and outputs. If the two expressions above are combined, their sectioning loops are fused into a single loop. The body of the fused sectioning loop for the code fragment

\[
k = \text{pcoord}(0);
\text{where} (k > 0) \{ 
\text{harmonic} = 1.0 / k;
\text{sum} = += \text{harmonic};
\}
\]

is transformed into the following, which computes a float scalar \text{ViC\_40}:

\[
\text{sum} = \text{ViC\_40};
\]
Note that the body of the loop computes the temporary variable used to hold context information, eliminating the need to read it from disk.

The optimizer operates on basic blocks containing out-of-core operations. A basic block consists of expressions and assignments with linear control flow. Data dependencies within a basic block form a dag. Vertices identify the results of the operations in the block, and edges connect operands to an operation. Any in-order traversal of the dag correctly evaluates the operations.

The dag is used to partition the basic block into subgraphs, each of which is a simple block, implemented with a sectioning loop. Within a subgraph, initial vertices are those which have no input edges, such as variable values. Final vertices are those which have no output edges, such as assignments to variables whose value is not used in the subgraph. Operations that potentially involve communication, such as reductions, left indexing, and subroutine calls, delimit simple blocks and must be either initial or final vertices. They are final vertices of the simple block that computes them, and they are initial vertices of the simple block that uses them. Such values are implemented with temporary variables that transmit their value from one block to another.

In the sample program above, we combine the parallel division and summation into one simple block, but the result of the summation is not available until the next simple block. When we include the dependency on \( \text{sum} \) in the program

```c
*ViC_..k.strip = ViC_.position + pcoord(0); /* evaluate expression */
*ViC_..30.strip = (*ViC_..k.strip > 0)
where (*ViC_..30.strip) {
  *ViC_..harmonic.strip = 1.0 / *ViC_..k.strip; /* evaluate expression */
  ViC_..40 += *ViC_..harmonic.strip; /* evaluate reduction */
}
```

the assignment to \( \text{normal} \) requires a second sectioning loop.

Likewise, the vertex for a \textit{volatile} operand or one that is aliased must be initial or final. In addition, for debugging purposes, a compiler flag forces every out-of-core operation into a separate simple block. In this case, no loop fusion occurs and debugging can proceed statement by statement.

Observe that context, which we can view as an implicit operand of every expression (except in the scope of an explicit \textit{everywhere}), motivates loop fusion even when it would otherwise be unprofitable. For example, in the absence of context, if two consecutive statements had no variables in common, we would avoid fusing their sectioning loops in order to maximize the in-core strip size. Larger strip sizes lead to faster I/O. If the statements share a context, however, fusing the loops obviates the need to read the context for the second statement and possibly even the need to write it to disk.

The optimizer also expands certain out-of-core constant expressions, such as the value \( pcoord(0) \) assigned to \( k \) above. Expressions expanded by the optimizer include simple arithmetic operations involving scalar constants and the intrinsic function \texttt{pcoord}.

An additional optimization avoids writing out-of-core variables that are no longer live, i.e., those that will not be read back. This optimization requires ViC\textsuperscript{*} to perform a data flow analysis beyond the scope of a basic block.
outofcore shape [N]series;  

float mean(float:series a);  

float:outofcore current normalize(float:outofcore current a);  

int:series calc(outofcore shape s);  

\[ \text{\texttt{ViC\_shape series} = \{ \$\texttt{ViC\_everywhere}, N, 1, \{N\} \}}; \]
\[ \text{\texttt{float mean(ViC\_data a)};} \]
\[ \text{\texttt{void normalize(ViC\_data *ViC\_result, ViC\_data a)};} \]
\[ \text{\texttt{void calc(ViC\_data *ViC\_result, ViC\_shape s)};} \]

**Figure 7:** Example function headers and the result of their processing.

## 8 Processing of functions and communication

This section describes how ViC* processes function declarations, parameters, and results. ViC* processes function definitions and function calls with out-of-core formal parameters and results; in-core parameters and results remain unchanged. Parameter and result declarations are transformed as described in Section 4. Statements in the function body are rewritten to operate on out-of-core data as described in Section 7. Function calls are processed to pass arguments and return results by value, in conformance to the C and C* convention.

Out-of-core shape and data parameters are replaced with the corresponding ViC\_shape and ViC\_data declarations, as shown in Figure 7. Out-of-core shape parameters and parameters using the shape current must be declared with the outofcore keyword. ViC* ensures that out-of-core data that is passed by value is copied by the caller. This copying may be combined in a simple block with other operations in the caller, or it can be achieved by calling a library subroutine, ViC\_Copy, to copy the data.

Instead of returning an out-of-core result by value, ViC* passes a pointer to an out-of-core result variable as an extra parameter. Within the function body, all return statements copy the return value to the result parameter. This assignment may be combined in a simple block with other computations. By using a result parameter, ViC* avoids an additional data copy by the caller.

Local variables and temporaries must be deleted when the function exits or returns. In-core data is allocated on the stack and is automatically reclaimed. Out-of-core data is persistent, and must be explicitly deleted by calling ViC\_Remove for each local variable at every exit point.

It is generally more efficient to pass out-of-core parallel data by reference, using pointers, than by value, which would entail copying the data. Admittedly, this style may increase the programming effort required to use out-of-core data. In some cases, however, different algorithms are more efficient for out-of-core data, making a distinct out-of-core version desirable. Function overloading in C* allows both versions to coexist.

ViC* processes all communication that involves out-of-core variables (accomplished by parallel left indexing) by generating calls to run-time library functions. This run-time library is an integral part of the virtual-memory package and implements efficient algorithms for special cases of communication [Cor92]. The ViC* library implements left indexing of out-of-core variables where the index is scalar, in-core parallel, or out-of-core. It also implements left indexing of in-core parallel variables when the index is out-of-core. The C* communication routines to\_grid, to\_torus, from\_grid, and from\_torus are also overloaded to support out-of-core data, such as the send operation \[ [.\text{-1}]\text{normal} = \text{normal} \] in the sample program.
9 Conclusion

ViC* supports parallel programming on large data sets. It takes advantage of the distributed memory model of C* to provide the convenience of in-core programming for data too large to fit in main memory. With a small extension to the C* language, this approach implements virtual memory for parallel data. ViC* gives C* programmers a migration path for applications that exhaust physical memory resources.

ViC* goes beyond a simple library interface. For large datasets, we expect the time spent performing I/O to exceed the time spent computing. ViC* analyzes program data flow and performs program transformations to reduce I/O demands. It calculates the amount of in-core data to make full use of available memory. ViC* fuses in-core sectioning loops to avoid repeated transfers of the same data. These loops can cross context boundaries. In some cases, ViC* recomputes expressions to avoid saving and recalling their values.

In addition, we expect ViC* to serve as a testbed for parallel I/O research. Because I/O is under the ViC*'s control, we can experiment with parallel I/O algorithms and implementations. Areas of investigation include tradeoffs between synchronous and asynchronous I/O [KKP94], out-of-core algorithms [Cor92], and parallel file systems [CK93].

Other extensions to ViC* may include optimizations of elemental functions [KF93]—those which require no parallel communication. We can evaluate an elemental function on an in-core strip, calling it within the body of a sectioning loop. For arbitrary communications using left indexing, we expect to categorize index values where possible by communications topology, such as grid, torus, transpose, and general permutation. There are special algorithms [Cor92] for these communication patterns.

File systems normally support persistent data. Program data, such as ViC* out-of-core data, is transient and disappears on program exit. ViC* ensures that such data is properly deleted on scope exit. Global out-of-core data must be deleted specially. Alternatively, ViC* out-of-core data might be used to support persistent variables or program checkpointing.

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References


A ViC* Output

This appendix shows the code ViC* generates for the sample program of Figure 1. Comments are added for clarity; ViC* normally only copies comments unchanged.

```c
#define N (1L<<40) /* N == 2**40 */

ViC_shape series = { &ViC_everywhere, N, 1, {N} };
ViC_data normal = { &series, 0, NULL};

void example()
{
    ViC_data harmonic = { &series, 0, NULL };
    float sum;
    ViC_data k = { &series, 0, NULL };

    /* with (series) */
    {
        ViC_shape *ViC_prev = ViC_current; /* save previous shape */
        ViC_current->context = ViC_context; /* save context */
        ViC_current = &series; /* point to current ViC_shape */
        ViC_context = ViC_current->context; /* take its context */

        /* generate harmonic series and compute sum */
        harmonic = 1.0/k;
        sum = += harmonic;
        */

        shape *ViC__stripshape = ViC__Stripshape( /* determine strip shape */
            sizeof(bool:current) +
            sizeof(float:current) +
            sizeof(int:current));

        with (*ViC__stripshape) { /* in-core shape */
            ViC__DCL(bool, 10, ViC__context); /* in-core context */
            ViC__DCL(float, harmonic, &harmonic); /* in-core data */
            ViC__DCL(int, k, &k);
            float ViC__40 = 0.0; /* reduction accumulator */
        }

        ViC__LOOP {
            ViC__READ(10);

            where (*ViC__10_strip) {
                *ViC__k_strip = ViC__position + pcoord(0);
            }

            where (*ViC__10_strip & ViC__k_strip > 0) { /* establish context */
                *ViC__harmonic_strip = 1.0 / *ViC__k_strip;
                ViC__40 = =*ViC__harmonic_strip;
            }
            ViC__WRITE(harmonic); /* write output data */
        }

        ViC__Free(); /* free in-core strips */
        ViC__CLOSE(k, &k); /* close data files */
        ViC__CLOSE(harmonic, &harmonic);
        ViC__CLOSE(10, ViC__context); /* close context */
        sum = ViC__40; /* reduction operation */
    }
```

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ViC__Freeshape(ViC__stripshape);  // delete shape */
}

/* use sum to generate normalized series
   normal = harmonic*(1.0/sum);
*/
{
  shape *ViC__stripshape = ViC__Stripshape(  // determine strip shape */
    boolsizeof(boolean:current) +
    boolsizeof(int:current) +
    boolsizeof(float:current) +
    boolsizeof(float:current));

with (*ViC__stripshape) {  // in-core shape */
  ViC__DCL(boolean, 12, ViC__context);
  ViC__DCL(int, k, &k);
  ViC__DCL(float, harmonic, &harmonic);  // in-core data */
  ViC__DCL(float, normal, &normal);

  ViC__LOOP {
    ViC__READ(12);  // in-core context */
    ViC__READ(harmonic);  // in-core data */

    where (*ViC__12_strip) {
      *ViC__k_strip = ViC__position + pcoord(0);
    }

    where (*ViC__12_strip & *ViC__k_strip > 0) { /* establish context */
      *ViC__normal_strip = *ViC__harmonic_strip * (1.0 / sum);
    }
    ViC__WRITE(normal);  // write output data */
  }

  ViC__Free();  // free in-core strips */
  ViC__CLOSE(normal, &normal);  // close data files */
  ViC__CLOSE(harmonic, &harmonic);
  ViC__CLOSE(k, &k);
  ViC__CLOSE(12, ViC__context);  // close context */
}

ViC__Freeshape(ViC__stripshape);  // delete shape */
}

to_grid(&normal, &normal, &normal, -1);  // grid communication */
ViC__current = ViC__prev;  // restore previous shape */
ViC__context = ViC__current->context;  // and context */
}