C++ programming language for an abstract massively parallel SIMD architecture

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Abstract. The aim of this work is to define and implement an extended C++ language to support the SIMD programming paradigm. The C++ programming language has been extended to express all the potentiality of an abstract SIMD machine consisting of a central Control Processor and a N-dimensional toroidal array of Numeric Processors. Very few extensions have been added to the standard C++ with the goal of minimising the effort for the programmer in learning a new language and to keep very high the performance of the compiled code. The proposed language has been implemented as a porting of the GNU C++ Compiler on a SIMD supercomputer.

1 Introduction

The aim of this work is to define and implement an extended C++ language to support the SIMD programming paradigm. Our goal is to add minimal extensions to the standard C++ in order to minimise the syntactical differences when porting standard C++ applications or writing new codes. Our decision to be always as close as possible to the standard lead to the definition of an extended C++ language with very few constructs to learn for C++ programmers, and relatively easy to use.

Using our language, the SIMD parallelism is efficiently achieved with traditional sequential programming plus a couple of new constructs (used to perform memory mapped internode communication and to inhibit execution of code on some processing nodes) and some knowledge of the native data types and their allocation. The programmer can thus focus on the realization of the algorithm and on the data distribution, which are the key points to exploit the parallel architecture.

The proposed language has been implemented as a porting of the GNU C++ Compiler for the APEmille parallel supercomputer. Some modifications of the GNU C++ Compiler have been introduced, as well as the complete redefinition of the back-end for the target machine. APEmille is a parallel SIMD supercomputer.

¹ Release 2.95.1
computer developed at INFN (Italian National Institute for Nuclear Physics) capable of peak performance of 1 Teraflop in a configuration with 2048 processing nodes.

The simplicity and low number of extensions to the standard language helped reaching the goal of efficiency of the executable parallel codes, main goal for any number crunching application running on a massively parallel supercomputer.

In this paper, we describe the proposed SIMD C++ language, and especially those aspects which extend the standard C++ syntax or semantics. Section 3 is devoted to this description. Section 2 explains the abstract SIMD architecture which we refer to, while section 4 reports on those works related to our either for the language used (extensions of C/C++) or for a similar target architecture or parallel paradigm. Section 5 contains the conclusions.

2 The Abstract SIMD machine

SIMD machines consists of synchronized processing elements with an associated unique control processor. The Control Processor (later, CP) broadcasts the same instruction stream to all processing elements. All processing elements execute the same instruction at each clock cycle on their own data. In the proposed architecture the processing elements are specialized processors for numeric applications: we will call them Numeric Processors or NPs. The NPs form an N-dimensional toroidal array. Each NP consists of an ALU, an own register file, a local memory and a local memory mass storage. There is no shared memory across the whole machine: communication among NPs is achieved through a memory mapping mechanism that allows each NP to access memory of its neighbours. The machine is SIMD and guarantees no conflicts in memory accesses.

2.1 Control Processor

The CP handles integer data types, executes branches, function calls, and generates memory address. Every instruction is sent by the CP to each NP in the machine, at the same clock cycle.

Global addresses are broadcasted to all NPs. They will use them to address their own memory.

2.2 Numeric Processor

NPs are specialized in numeric instructions, in fact they natively support floating point data types – scalar (both single and double precision), vector/complex (couple of single precision) and the integer data type.

NPs, in order to perform conditional execution, can test local conditions, and, when they are not met, can disable the effect of the following numeric instructions. We call the conditional test a where instruction.

CP can also make all NPs test their local conditions. Then it can perform a global branch if any, all or none of the NPs has met the condition.
NPs can address their own memory using the global address generated by
the CP and, eventually, adding a local offset.

3 Proposed SIMD C++ language

In this section we describe our extended C++ analyzing all the aspects more re-
lated to parallelism. Subsection 3.9 contains a resume of the main characteristics
and discusses general topics.

3.1 Types, Declarations and Allocation

Basic Data Types With basic data types or basic types we refer to the types
natively supported by the language, as int or float. The C++ language pro-
posed in this paper includes all the basic data types supported by the illustrated
abstract SIMD machine. Namely:

int, float, double, complex, vector, localint

The localint data type are integer variables allocated in the numeric processors
(see later), while the types vector and complex represent a pair of float and are
treated as native types by our abstract machine. Pointers, arrays and function
pointers are supported for every type and every level of indirection.

These types are all signed. All the "standard" C++ types (e.g.: long long,
long double, char, etc. and all unsigned types) could be supported, perform-
ing software emulation for those not supported by the physical machine.

Declaring variables is absolutely identical to standard C++. It is also pos-
sible to declare new types with the typedef keyword just as in C++, with the
standard rules and no limitation.

Allocation The variables declared are allocated in the Control Processor (CP)
or in the Numeric Processor (NP) depending on their type. We divide the ba-
sic types into two groups: the Control Processor types (int, pointers) and the
Numeric Processor types (float, double, vector, complex, localint).

CP variables are allocated in the (unique) Control Processor, so there is just
one instance of them; NP variables are allocated in each NP data memory, and,
most important, at the same location in every one: so there are multiple in-
stances of numeric variables. This is the essence of the SIMD programming paradigm,
and implies a very important fact: memory images of NPs are all identical; each
allocation, both static and dynamic, is the same for every NP.

Arrays of any type are allocated in the same processor of the base type. For
example, the array
double a[100000];
is allocated in the NPs’ memories. However the base of the array, which is known at compile time, is a pointer, and so it is handled by the CP.

The allocation mechanism is automatic and controlled by the compiler; there is no way and no reason for the programmer to alter it. On the other hand data distribution is left to the programmer. We will discuss this topic in subsection 3.8.

3.2 Expressions

Expressions within the same type Handling expressions among variables of the same type is not ambiguous, because they are allocated in the same kind of processor so code for “that” processor will be generated to handle them. For example:

| CP allocation | int i, j, k;          |
|               | double a, b, c;       |
|               |                       |
| CP code       | i = j+1;              |
|               | a = 1.0;              |
|               | b = a*c-b;            |
|               | k++;                  |

Promotions

|      | int | CP ptr | NP ptr | float | double | vector | complex | localint |
|------|-----|--------|--------|-------|--------|--------|---------|----------|
| int  | yes | yes    | yes    | yes   | yes    | yes    | yes     | yes      |
| CP pointer | yes | yes     | yes   | no    | no     | no     | no      | yes      |
| NP pointer | yes | yes     | yes   | no    | no     | no     | no      | no       |
| float | no  | no      | no     | yes   | yes    | yes    | yes     | yes      |
| double | no  | no      | no     | yes   | yes    | yes    | yes     | yes      |
| vector | no  | no      | no     | yes   | yes    | yes    | yes     | yes      |
| complex | no  | no      | no     | no    | no     | yes    | no      | no       |
| localint | no  | no      | yes   | yes   | yes    | yes    | yes     | yes      |

Table 1. Allowed Promotions

Mixed-types expressions They are handled by promoting types, or by explicit cast by the programmer. There are specific rules about cast and promotions.

- cast/promotions from CP to NP types are ALWAYS allowed.
- cast/promotions from NP to CP types are NEVER allowed.
- cast/promotions between two types of the same group are allowed depending on the specific types.
It is obvious that a cast/promotion from a CP type to NP generates multiple instances of one value.

### 3.3 Multiple Addressing

As stated before, the abstract SIMD machine includes the ability to add a local offset when accessing local NP memory, so every NP could access a different location in memory. This is realized with the `localint` variables, that are integers allocated in the NPs. These values can be used to add a local displacement when accessing local memory.

A pseudo function `localoffset()` can be called with a `localint` argument to set the local offset for the following memory access.

```c
int i;
localint li;
float r, a[100];
// ...
localoffset(li);
r = a[i];
```

In the example above, access in array `a` is at index `i + li`.

### 3.4 Type Constructors: Structs, Classes and Unions

It is possible to declare a new type using `struct`, `class` or `union` as in standard C++. Structs and classes can contain data fields of any other data type (both CP types and NP types), while unions must contain fields associated to the same kind of processor (only CP or only NP), due to allocation reasons, as explained before.

```c
class Mixed {
    int a;
}```
float x;
public:
    Mixed (int aa, float xx) : a(aa), x(xx) {};

Each field is allocated in the respective processor so that multiple instances of numeric field exist. The effort to address them and to keep pointers consistent is made by the compiler. Fields must be accessed directly with pointers: incrementing and decrementing pointers to "navigate" through a struct or class could generate unpredictable results because the object is allocated on different memories. The space allocated is compacted, so that only the necessary size is allocated in each kind of processor.

3.5 Object Oriented Features:
Encapsulation, Inheritance, Polymorphism

Encapsulation is handled as in standard C++ with no other extension nor limitation. Field allocation follows what stated in 3.4. Methods are called passing them the invocation object as an hidden argument. The same method is executed by each NP.

Also Inheritance and Polymorphism have no extensions nor limitations. Non-virtual base class members are inserted in the CP or NP instance layout of the object after their type class. Virtual base class members and virtual classes information are inserted into the CP instance of the object: in fact they are pointers.

3.6 Communication

Communication among Numeric Processors is achieved through memory mapping. The proposed C++ language allows to address an array element in a remote NP by summing a constant to the array index or to the pointer that would be used for local access. Different pre-defined constants are associated to neighbour NPs. These constants specify the relative position of the NP to be accessed with respect to the current NP. The constants are generated and handled on the CP, so they are the same for all NPs. The following example shows communication between NPs:

    float r, v[100000];
    r = v[3+XPLUS_NP];  // each NP accesses the 3rd element of
                        // the nearest neighbour on the x axis
                        // in the positive direction

The constant XPLUS_NP is machine dependent.

It is possible to use a remote object as parameter or invocation object of a method. In this way, a code like:
```cpp
class C {
public:
    float x;
    void f(float y) { x = y; }
};

int main() {
    float a;
    C v[10];
    // ...
    v[0+XPLUS_NP].f(a);
    // ...
}
```

assigns to the x field of the v[0] object on each node the value of a on the adjacent (XMINUS_NP) node.

### 3.7 Local Conditions

The instruction flow being unique, it is possible to branch only when global conditions (conditions on the CP) are met. Conditions on local variables (on NPs) can be handled with the `where-elsewhere` keywords. Conditioned code will be executed only by those NPs that met the condition. All the other NPs will execute NOPs. CP instructions inside a `where` block, on the other hand, are always executed. `where-elsewhere` are used just like `if-else`, as shown in the following example.

```cpp
int i;
double x,y;
// ...
where (x != 0.0) {
    y = 1/x;
}
elsewhere {
    y = 0;
}
```

### 3.8 Examples of implementation of SIMD programs

When writing a program for a SIMD machine using the proposed C++ extensions, the “SI” part of the SIMD paradigm is realized using a single instruction stream, as the C++ language naturally does; the “MD” part of SIMD is achieved allocating multiple instances of the numeric variables.

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2 In our implementation, these are not keywords but function names.
The initial loading of different data in each Numeric Processor data memory is made by the operating system, while the slicing of a big array into the NPs must be determined by the programmer.

For example, suppose that the problem needs to handle an array of $10000 \times 10000$ elements, and that the target machine has a 2D square topology with $10 \times 10 = 100$ Numeric Processors. The programmer will declare a $10000 \times 10000$ array (and every NP will have its own instance of this array, that represents a slice of the big array). A very trivial example of code that implements the sum of two $10000 \times 10000$ elements arrays can be useful to explain the parallelization mechanism and the data distribution:

```c
int main()
{
    const int dimx = 1000;
    const int dimy = 1000;
    const int size_per_node = dimx*dimy;

    float m1[dimx][dimy], m2[dimx][dimy], m3[dimx][dimy];
    const char *filename = "myfile.data";
    // ...
    distributed_load(m1, filename, size_per_node);
    distributed_load(m2, filename, size_per_node);
    for (int i=0; i<dimx; i++)
        for (int j=0; j<dimy; j++)
            m3[i][j] = m1[i][j] + m2[i][j];
    // ...
}
```

Numeric instructions will be executed in parallel by the Numeric Processors on their local data, while Control Processor will execute flow control, integer instructions and will generate memory addresses. The `distributed_load()` and `distributed_store()` functions perform machine dependent system calls supposed to load and store data in the appropriate way.

### 3.9 General remarks on the language proposed

The proposed C++ is very similar to the standard C++, is easy to learn, to use and to debug, produces highly efficient executable codes, and can be used in a professional environment.

The most important aspect of the proposed language is that it is a minimal extension to the C++ standard. This is a key feature as we want the programmer to concentrate on the application development rather than paying attention to implementation aspects.

Our language strictly conforms to the machine architectural characteristics in order to fully exploit the simplification that the SIMD synchronous structure
and the memory mapped internode communications introduce in the task of writing the parallel algorithm.

As a result, there is no need to develop multi-threaded programs nor to use any special communication library.

Finally, object distribution is obtained by the simple allocation model described above. All objects are replicated on each processing element and invocation of a method is executed on all NPs (or on the subset of them satisfying an eventual WHERE condition).

4 Related work

In this section we compare our language to a couple of parallel C/C++ extensions and to High Performance Fortran, which is the standard for data parallel applications.

HPC++ \cite{7,8} is a set of class libraries and tools that extend the C++ language. It also has a set of runtime systems that are required for remote access. It refers to a very general architectural model, so it can be used on a variety of machine architectures. There are two main execution modes for programs written in HPC++:

1. multi-thread shared memory mode, suitable for coarse-grained applications with some particular collective operations for thread synchronization.
2. Single Program Multiple Data (SPMD) mode, in which many copies of the same program run on the n processing nodes. This mode is similar to using C/C++ with MPI or PVM. The programmer must manage the data distribution and the synchronization of processes.

HPC++ has thus a totally different approach compared to our one, and this approach is not applicable to our language architecture which is focused on single threaded programs.

pC++ \cite{9} is a C++ extension that provides a thread-based programming model and a simple way to encapsulate SPMD code in it, together with a mechanism for data distribution similar to the one adopted in HPF (see below). The key concept of this extension is the collection of objects. It is possible to invoke a method on an entire collection or on a part of it. The compilation of pC++ code is achieved as a translation into standard C++ by a preprocessor.

The HPF \cite{10} programming model has the following key points:

1. single threaded control;
2. global namespace, low-level of data distribution and remote communication details hidden to the programmer;
3. loosely synchronous: synchronization of program execution on different nodes is accomplished only at special points (e.g. the completion of a loop) and not instruction by instruction;
4. parallel operations: operations on array elements executed at the same time over all nodes.
HPF extends the Fortran language adding compiler directives, libraries and new language constructs.

The most relevant compiler directives to our purposes are those related to data distribution. This is accomplished in three steps: in the first step an alignment is defined for arrays, in the second step aligned data are mapped on a abstract set of processors and finally this set is mapped onto physical processors. This is quite different from our approach as we force the programmer to take care of allocation of large matrices as described above. In particular we rely on operating system calls to perform something similar to the BLOCK and DEGENERATE distribution types.

A similarity between HPF and our language is the specification of locally conditioned code execution via the WHERE statement, although the HPF version accepts logical-array arguments while ours accepts any logical condition between NP data. Other parallel constructs, such as FORALL, are not provided by our language.

HPF is the parallel extension to a standard language that, compared with the other two, best matches with our approach.

5 Conclusions

The next topics to be analyzed will include exception handling, RTTI (Run Time Type Information) and namespaces.

Our implementation of the compiler based on a porting of the GNU CC compiler on the APEmille architecture is currently under test. We plan to discuss our implementation in a further paper.

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