Streaming Networks for Coordinating Data-Parallel Programs

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Abstract. A new coordination language for distributed data-parallel programs is presented, call SNet. The intention of SNet is to introduce advanced structuring techniques into a coordination language: stream processing and various forms of subtyping. The talk will present the organisation of SNet, its major type inferencing algorithms and will briefly discuss the current state of implementation and possible applications.

Data-parallel programming languages such as Nesl, Zpl, Sisal, or Single-Assignment C (known primarily as SaC) are known to be suitable for creating highly efficiently executable concurrent code for numerical applications. Instead of relying on programmer-specified explicit annotations as required for Hpf or a library extension as is the case with MPI-based or OpenMP-based solutions, these programming languages are designed in a way that allows compilers to derive concurrency implicitly from homogeneous operations on large arrays.

More recent work in the context of SaC demonstrates that not only does the data-parallel approach raise the level of abstraction in specifying numerical applications, but it also permits compiler technology to be developed that produces code competitive with that of low-level Fortran code. SaC programs can be written in a highly abstract style similar to specialised array programming languages such as Apl or J. This level of abstraction improves code reuse and maintainability of programs since the programmer can focus on the functionality of individual components of a program rather than being constantly driven by performance considerations [14]. Despite being less aware of the performance issue, the programmer's functional specifications can automatically be compiled into code whose sequential runtime is competitive with that of low-level Fortran programs where the programmer has to be aware of the performance issues continually. Thanks to the sophisticated compiler technology developed within the SaC project, SaC programs can be compiled into multithreaded code without any source modification [6]. As sequential runtimes are competitive with sequential low-level code, so too the multithreaded code produced by our compiler is very effective: the speed up for SMP platforms is almost linear in the number of processors up to $p = 8$ and in many cases beyond.

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One has to admit, however, that the concurrency that can be exploited by the data parallel approach is limited to homogeneous operations on arrays. Although these prevail within the component code for numerical applications, when components are joined together, other forms of concurrency become prevalent, which are better captured by pipelining, process farming and arbitrary message passing. These forms of concurrency can not always be derived from a sequential application code, since they tend to be strongly application-dependent. There is a whole host of "parallel algorithms" capturing problem-specific data migration and load balancing, of which perhaps the most convincing example is provided by molecular dynamics and plasma particle simulations, see, for example, papers [10,3]. The methods being used rely upon the knowledge of computational properties, such as relative cost of various components, and co-location requirements. For instance, the designer of a particle-in-cell simulation is naturally aware that the main computational cost is in pushing particles under the influence of electromagnetic forces, hence load balancing should focus on that, while field calculations are always assumed to be much cheaper. It is hardly realistic at present time to expect any compilation system to be able to derive this kind of information from sequential (or even purely functional) code.

Process concurrency is difficult to deal with in the framework of a programming language. If properly integrated into the language semantics, it complicates and often completely destroys the properties that enable the kind of profound optimisations that make compilation of array programs so efficient. One solution to this problem, which is the solution that we align ourselves with, is the use of so-called coordination languages. A coordination language uses a readily-available computation language as a basis, and extends it with a certain communication/synchronisation mechanism thus allowing a distributed program to be written in a purely extensional manner. The first coordination language proposed was Linda [5,4], which extended C with a few primitives that looked like function calls and could even be implemented directly as such. However an advanced implementation of Linda would involve program analysis and transformation in order to optimise communication and synchronisation patterns beyond the obvious semantics of the primitives. Further coordination languages have been proposed, many on them extensional in the same way, some not; for the state of the art, see a survey in [12] and the latest Coordination conference [8].

The emphasis of coordination languages is usually on event management, while the data aspect of distributed computations is not ordinarily focused on. This has a disadvantage in that the structuring aspect, software reuse and component technology are not primary goals of coordination. It is our contention that structuring is key in making coordination-based distributed programming practically useful. In this paper we propose several structuring solutions, which have been laid in the foundation of the coordination language SNet. The language was introduced as a concept in [16]; the complete definition, including semantics and the type system, is available as a technical report [17].

The approach proposed in SNet is based on streaming networks as introduced in foundation work [9,1,7], see also more recent work on stream network

semantics [2] and language design [11]. The application as a whole is represented as a set of self-contained components, called "boxes" (SNetis not extensional) written in the data-parallel language SaC. SNet deals with boxes by combining them into networks which can be encapsulated as further boxes. The structuring instruments used are as follows:

- Streams. Instead of arbitrary communication, data is packaged into typed variant records that flow in a sequence from their producer to a single consumer.
- Single-Input, Single-Output(SISO) box and network configuration. Multiple connections are, of course, possible and necessary. The unique feature of SNet is that the multiplicity of connection is handled by SNet combinators so that a box sees a single stream of records coming in. The records are properly attributed to their sources by using types (which include algebraic types, or tagged, disjoint unions). Similarly, the production of a single stream of typed records by a box does not preclude the output separation into several streams according to the type outside the box perimeter.
- Network construction using structural combinators. The network is presented as an expression in the algebra of four major combinators (and a small variety of ancillary constructs): serial (pipelined) composition, parallel composition, infinite serial replication (closure) and infinite parallel replication (called index splitter, as the input is split between the replicas according to an "index" contained in data records). We will show that this small nomenclature of tools is sufficient to construct an arbitrary streaming network.
- Record subtyping. Data streams consist of flat records, whose fields are drawn from a linear hierarchy of array subtypes [15,18]. The records as wholes are subtyped since the boxes accept records with extra fields and allow the producer to supply fewer variants than the consumer has the ability to recognise.
- Flow inheritance. Due to subtyping, the boxes may receive more fields in a record than they recognise. In such circumstances flow inheritance causes the extra fields to be saved and then appended to all output records produced in response to a given input one[1]. Flow inheritance enables very flexible pipelining since, on the one hand, a component does not need to be aware of the exact composition of data records that it receives as long as it receives sufficient fields for the processing it is supposed to do; and on the other, the extra data are not lost but passed further down the pipeline that the components may be connected by.
- Record synchronizers. These are similar to I-structures known from dataflow programming. SNet synchronisers are typed SISO boxes that expect two records of certain types and produce a joint record. No other synchronisation mechanism exists in SNet, and no synchronisation capability is required of the user-defined boxes.

[1] This is a conceptual view; in practice the data fields are routed directly to their consumers, thanks to the complete inferability of type in SNet.

– The concept of network feedback in the form of a closure operator. This connects replicas of a box in a (conceptually) infinite chain, with the input data flowing to the head of the chain and the output data being extracted on the basis of fixed-point recognition. The main innovation here is the proposal of a type-defined fixed point (using flow inheritance as a statically recognisable mechanism), and the provision of an efficient type-inference algorithm. As a result, SNet has no named channels (in fact, no explicit channels at all) and the whole network can be defined as a single expression in a certain combinator algebra.

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