Language and Run–time Support for Network Parallel Computing

Peter A. Dinda David R. O'Hallaron Jaspal Subhlok* Jon A. Webb Bwolen Yang

School of Computer Science
Carnegie Mellon University
Pittsburgh PA 15213

Abstract

This paper describes NetFx, the extended Fx compiler system for network parallel computing. NetFx uses the Fx model of task parallelism to distribute and manage computations across the sequential and parallel machines of a network. The central problem in compilation for network parallel computing is that the compiler is presented with a heterogeneous and dynamic target. Our approach is based on a novel run–time system that presents a simple communication interface to the compiler, but uses compiler knowledge to customize communication between tasks on heterogeneous machines over complex networks. The compiler generates code for data parallel modules with point–to–point transfer of distributed data sets between modules. This allows the compiler to be portable and enables communication generation without knowledge of exactly how the modules will be mapped at run–time, and what low level communication primitives will be used. The compiler also generates a set of custom routines, called distribution functions, to translate between different data distributions. The run–time system performs the actual communication using a mix of generic and custom distribution functions depending on run–time parameters like the type and number of nodes assigned to the communicating modules and the data distributions of the variables being communicated. This mechanism enables the run–time system to exploit compile–time optimizations, and enables the compiler to manage foreign modules that use non–standard data distributions. We describe the NetFx programming model, the communication interface, how NetFx programs are compiled to the interface, and the issues in implementing the interface.

1 Introduction

New networking technologies like HiPPI and ATM have made it possible to implement efficient network parallel applications. Because of considerable improvements in the latency and bandwidth characteristics of networks, the domain of applications that can benefit from network parallel computing has become much larger, including diverse fields like scientific simulations, real-time applications and real-world modeling. However, standard parallel languages like High Performance Fortran (HPF) [6] offer little support for network parallel computing. Without such support, the construction of an efficient, scalable, and environment–independent network parallel application is a difficult and error–prone task in which the applications programmer must wear many hats, including that of the network specialist.

The goal of our research is to make it possible to program network parallel applications in an easy and efficient way. Compiling for a variety of machines across a network presents several new challenges. This paper shows how parallelism inside a single machine and across a set of machines can be expressed in a uniform framework. We also present the design of a compiler and a run–time system that enables efficient generation of programs for network parallel computing.

The programming model we use combines task and data parallelism. Procedures in an application are data parallel and each procedure is mapped to a homogeneous set of nodes, which may be different nodes of a large parallel machine or a cluster of workstations. Different procedures are placed on different sets of nodes on the network and the compiler manages the communication between them.

The most challenging part of compilation for a network is generating efficient communication. The most efficient communication interface across a network is typically different from the communication interface between the nodes of a parallel machine, hence the compiler has to manage multiple communication paradigms. More important, the

---

[*] Corresponding author. (`jass@cs.cmu.edu`, (412) 268 7893)

network environment is expected to be dynamic. Run–time load balancing is important even for applications with a static computation structure since the external load on different machines can vary. This means the compiler has limited information about the run–time environment during code generation.

For generating efficient and portable communication in a dynamic run–time environment, it is important to distinguish between the aspects of the communication that are constant for the duration of the execution and those that are varying and may be known only at run–time. In our model, the program is partitioned into modules and each module is mapped to a set of nodes. The communication steps between modules are a property of the program and determined at compile time, while the actual low–level communication calls may depend on the run–time environment.

Our solution to generating efficient communication involves defining an inter–module communication interface. This interface provides mechanisms for transferring data between modules that are mapped on groups of nodes. The compiler generates code for this communication interface and the run–time system ensures that appropriate communication calls are generated. The compiled program is portable across the machines and network protocols supported by the run–time system.

The key new idea is that the interface decouples the compilation from generation of low level communication which is essential for a network environment, yet provides a mechanism for the compiler to customize the behavior of the run–time communication system. This mechanism allows the run–time system to exploit compile–time communication optimizations, and also allows the compiler to manage foreign modules that use non–standard data distributions.

We are developing a compiler system called NetFx to validate our approach. NetFx is based on the Fx compiler system [4], which extends a data parallel language based on HPF with task parallelism. We begin by motivating the need for network parallel computing with a set of example applications and then describe the NetFx system.

2 Motivation for network parallel computing

Different parts of a large application typically have different requirements for resources like I/O devices, sensors, processing power, communication bandwidth, memory, and software tools. Attempting to satisfy all of these resource requirements in a single computing platform can be impractical or even impossible. An attractive alternative is to run the different parts of the application on the appropriate platforms and use a high–speed network to transfer results back and forth between the different parts. We refer to this type of computation as *network parallel computation*.

This section illustrates the motivation for network parallel computing with four applications: (1) a *real–world modeling* application where inputs are acquired from a camera system, processed on a large parallel system, and displayed remotely, (2) an *air quality modeling* application where different steps of the computation have different processing and communication requirements, (3) an *earthquake ground motion modeling* application where the results are computed on a large parallel system and visualized on a graphics workstation, and (4) a *real–time embedded system* constructed from commercially–available rack–mounted array processor boards.

2.1 Real–world modeling

High performance computers and their programming tools have traditionally been applied to problems in scientific modeling, including simulation analysis. A group of researchers at Carnegie Mellon is applying these same systems and tools to problems in *real–world modeling*, which means three–dimensional shape modeling of objects and environments in the real world by direct observations using computer vision techniques. Success of this approach could lead to, for example, replacement of complex and specialized sensory systems based on laser range–finding technology by much simpler, more flexible and scalable, but computationally more expensive, systems like stereo vision. In real–world modeling applications the sensor system plays a key role. In some situations (e.g., imaging moving objects) it is necessary to capture imagery at video rate (30 Hz) or faster. Capturing data at this high rate is complicated by the need to synchronously access several cameras[1]. In other situations (e.g., imaging building interiors) speed of image capture is not so important but the imaging system must be portable.

These conflicting requirements can be met through the application of modern networking technology. The system we envision is illustrated in Figure 1. The camera system is a detachable unit, and can be attached either to

---

[1] In recent past, the most significant advances in stereo vision accuracy and reliability have come from the introduction of multiple cameras.

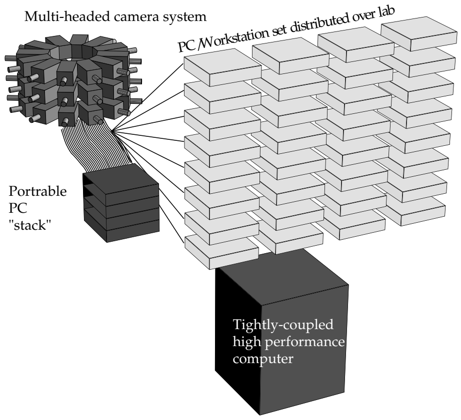


Figure 1: Real-world modeling system

a large number of workstations, giving a high frame capture rate, or to a smaller number of portable workstations or PCs, giving portability at the expense of speed. Once the images are captured, they are transformed into stereo vision data through the application of parallel stereo vision programmed in Fx, which can then be executed on the workstations themselves or on powerful tightly–coupled high performance computers. The resulting range imagery is then transformed into a three–dimensional model, which is another Fx program, and the resulting model can then be stored to disk or displayed remotely. NetFx implementation will allow us to program the entire framework including communication across the network in a uniform portable manner.

2.2 Air quality modeling

As part of a Grand Challenge grant on heterogeneous computing for large scale environmental modeling, researchers at Carnegie Mellon have adapted the airshed environmental model application [7] to run on parallel systems. The application consists of repeated application of three data parallel steps. The first step, reading input data from storage and preprocessing it, is I/O intensive. The second step, computing the interaction of different chemical species in the atmosphere, exhibits massive parallelism and little communication. The third step, computing the wind–blown transport of chemical species, has significant parallelism and communication. Each of these steps is suited to a different class of machine. For example, an Fx implementation of the chemistry step runs as fast on four Ethernet–connected DEC Alpha workstations as on 32 nodes of an Intel Paragon since the relatively slow communication is not an important factor, but the transport step is expected to be more sensitive to the parameters of the communication system. Further, the input step is best run concurrently with the other stages. A NetFx implementation will allow us to use a single high level program for the entire application and the ability to use different mappings for execution.

2.3 Earthquake ground motion modeling

As part of a Grand Challenge grant on earthquake modeling, researchers at Carnegie Mellon are developing techniques for predicting the motion of the ground during strong earthquakes. The computation consists of two distinct steps: simulation and visualization. The simulation step uses a large, sparse, and irregular finite element model to generate a sequence of displacement vectors, one vector per time step. The visualization step manipulates the displacement vectors and produces a graphical display. The simulation step requires access to large amounts of memory, computational power, and low–latency high–bandwidth communications, while the visualization step requires access to a bit–mapped display and, for the more complex 3D models, a graphics accelerator. The natural partitioning of this application is to run the simulation step on a large tightly–coupled parallel system, and to run the visualization step on a graphics workstation.

2.4 Real–time embedded systems

Economic realities have created a pressing need for embedded systems that are built with commercial off–the–shelf components. The basic building block is typically a commercial array processor board that consists of a fixed number of processors connected by a fast onboard switch. For larger systems, multiple boards are mounted in a rack and connected by a bus or ring structure. For still larger systems, multiple racks are connected by a commercial network like FDDI or ATM.

These systems are used for real–time applications like sonar and radar, where the processing typically consists of reading from one or more sensors, and then manipulating the inputs in a sequence of stages. Each stage must be assigned enough processing resources to match the throughput and latency requirements of the overall system. An application that needs multiple racks to meet its real–time requirements will of necessity be a network parallel computation.

3 Programming model for NetFx

The basic programming model provides support for task and data parallelism and is not changed from Fx [4, 10]. Support for data parallelism is similar to that provided in High Performance Fortran (HPF) and is described in [8, 12]. Task parallelism is used to map data parallel subroutines onto different, possibly heterogeneous, groups of nodes. We outline how task parallelism is expressed in NetFx and illustrate how it is used to exploit coarse grain parallelism.

3.1 Task parallelism

Task parallelism is expressed solely using compiler directives and no new language extensions are introduced. To simplify the implementation, the current version of Fx relies on the user to identify the side effects of the task–subroutines and to specify them. Directives are also used to guide the compiler in mapping the program which is important for performance and also to ensure that tasks execute on computers for which the compiled versions are available. We describe the directives that are used to express task parallelism and illustrate their use. We use the FFT–Hist kernel as an example program. This program takes a sequence of arrays as input, and for each input array, it performs a 2D FFT by performing a set of 1D FFTs, first on columns and then on the rows, followed by histogram analysis.

Parallel sections

Calls to task–subroutines are permitted only in special code regions called *parallel sections*, denoted by a `begin parallel/end parallel` pair. For example, the parallel section for the FFT–Hist example has the following form:

```
c$      begin parallel
        do i = 1,m
           call colffts(A)
c$         input/output and mapping directives
           call rowffts(A)
c$         input/output and mapping directives
           call hist(A)
c$         input/output and mapping directives
        enddo
c$      end parallel
```

The code inside a parallel section can only contain loops and subroutine calls. These restrictions are necessary to make it possible to manage shared data and shared resources (including nodes) efficiently. Every task–subroutine call inside a parallel section corresponds to a (possibly data parallel) *task* that can execute in parallel with other tasks subject to dependence constraints.

A parallel section introduces a data parallel thread for each task–subroutine inside it. Outside the parallel section, the program executes as a single data parallel thread.

Input/output directives

The user includes `input` and `output` directives to define the side–effects of a task–subroutine, i.e., the data space that the subroutine accesses and modifies. Every variable whose value at the call site may potentially be used by the called subroutine must be added to the input parameter list of the task–subroutine. Similarly, every variable whose value may be modified by the called subroutine must be included in the output parameter list. The variables in the input and output parameter lists can be distributed or replicated arrays, or scalars.

For example, the input and output directives for the call to `rowffts` have the form:

```
           call rowffts(A)
c$         input (A), output (A)
c$         mapping directives
```

This tells the compiler that the subroutine `rowffts` can potentially use values of, and write to the parameter array `A`. As another example, the input and output directives for the the call to `colffts` has the form:

```
           call colffts(A)
c$         output (A)
c$         mapping directives
```

This tells the compiler that subroutine `colffts` does not use the value of any parameter that is passed but can potentially write to array `A`

Mapping directives

Labeling task–subroutine calls and supplying input/output information is sufficient for the compiler to generate a correct parallel program. However, the performance of the program largely depends on how the task–subroutines are mapped onto the available computation resources on the network. The possible mappings are constrained by the availability of data parallel implementations of different task–subroutines for different architectures, memory requirements of the task–subroutines, and physical location of devices like frame buffers. Ideally NetFx should be able to automatically map the program for correct execution and best possible performance, but that is a hard problem and NetFx is not able to do it except in some simple situations [11]. In general, the programmer has to supply the mapping information.

The mapping information specifies where each of the task–subroutines should execute. The details of the mapping directives are somewhat cumbersome and machine specific and we will not describe them here. For example, when mapping a task–subroutine to a network of workstations, it may be necessary to specify the names of the workstations to be used as a node, but when mapping to a part of a massively parallel machine like the Intel Paragon, it may be sufficient to specify the number of nodes to be used.

3.2 Programming coarse grain parallelism

NetFx allows the programmer to use fine grain data parallelism as well as coarse grain task parallelism. We illustrate how the task parallelism directives described above are used to exploit common forms of coarse grain parallelism.

Task pipelines

In image and signal processing programs , the main computation often consists of repeatedly executing an acyclic task graph. A simple example of such a program is the FFT–Hist example program, which we now present with directives:

```
c$      begin parallel
        do i = 1,m
           call colffts(A)
c$         output (A)
           call rowffts(A)
c$         input (A), output (A)
```

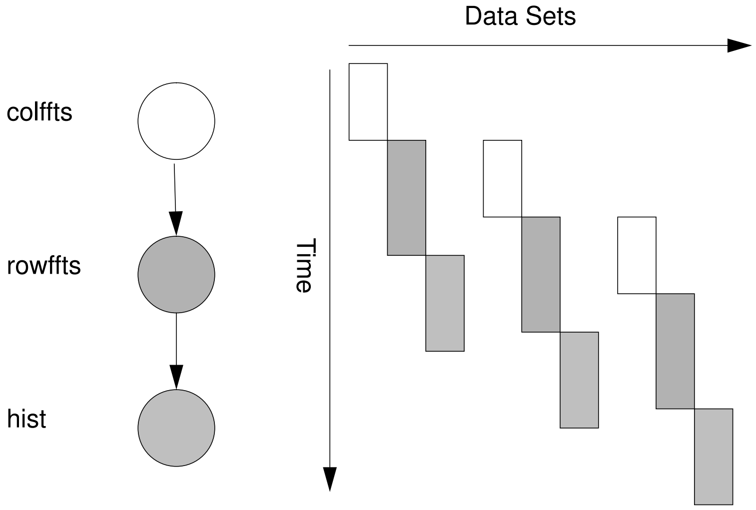


Figure 2: Dependences and coarse grain parallelism in FFT-Hist

```
               call hist(A)
c$             input (A)
            enddo
c$          end parallel
```

In FFT–Hist, all data dependences in the program are forward and loop independent. Task–subroutine *colffts* reads input, computes and sends output data set to *rowffts*, which receives the data set, computes, and sends the output data set to *hist*, which computes the final output. This allows an earlier stage, say *colffts* to process a new data set while *rowffts* is processing the previous data set, allowing coarse grain pipeline parallelism as shown in Figure 2. In related work, we have argued that such parallelism can be exploited efficiently and profitably for many applications including narrowband tracking radar and multibaseline stereo [9].

Communicating tasks

In many scientific applications, different subroutines can execute in parallel, but need to transfer or exchange data between invocations. For example, two routines *fproca* and *fprocb* may work on different parts of a data structure and exchange boundary elements between successive invocations. A task parallel program that expresses this computation is as follows:

```
c$          begin parallel
            do i = 1,m
               call fproca(A, boundA, boundBx)
c$             output (boundA), input (boundBx)
               call fprocb(B, boundB, boundAx)
c$             output (boundB), input (boundAx)
               call ftransfer(boundA, boundB, boundAx, boundBx)
c$             input (boundA, boundB) output (boundAx, boundBx)
            enddo
c$          end parallel
```

We show the input/output directives only for the boundary elements for the purpose of illustration. The task dependence graph for this computation is shown in Figure 3. There is no direct dependence between task–subroutines *fproca* and *fprocb*, but they have a loop carried dependence on *ftransfer* due to variables *boundAx* and *boundBx* respectively. Task–subroutine *ftransfer* has a loop independent dependence on *fproca* and *fprocb*, due to variables *boundA* and *boundB*. Thus, the iterations of *fprocA* and *fprocB* execute in parallel and effectively exchange boundary elements using task-subroutine *ftransfer*. The computation schedule is illustrated in Figure 3. Note that the results obtained by task parallel execution are consistent with sequential execution.

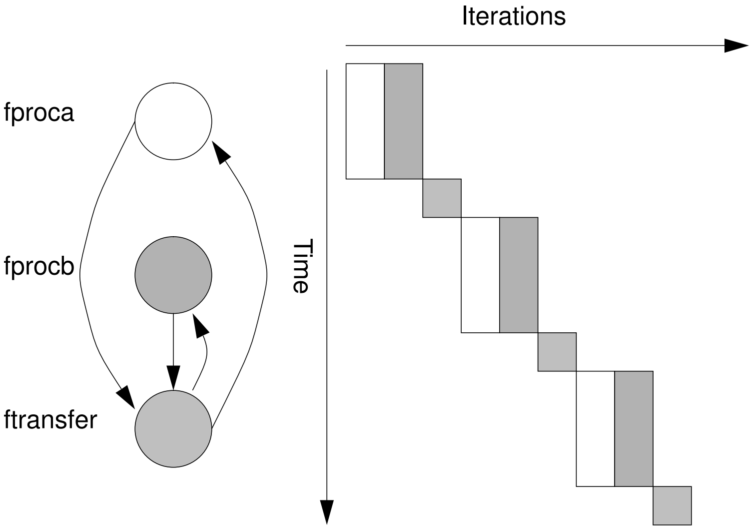


Figure 3: Dependences and coarse grain parallelism for a program with data exchange between parallel iterations

3.3 Compilation

The compiler uses a data flow algorithm to analyze the dependences caused by input/output variables and precisely determines the data movement between tasks. The basic paradigm is that the results obtained must always be consistent with sequential execution. It then uses the mapping information to group task–subroutines into *modules*. All task–subroutines inside a module are mapped to the same set of nodes. A module repeatedly receives input, computes, and generates output.

The compiler generates calls to the run–time system for communication between modules, and may also generate distribution functions that the run–time system uses to translate between data distributions. Inter–module communication management is done jointly by the compiler and the run–time system and the details are discussed in the next section. The involvement of the run–time system is necessary since the compiler may not know the mapping of the modules to the available nodes, the current distribution of data on a remote module, or the status of the (possibly general purpose) network at run-time. This information may change unpredictably for a variety of reasons, including load balancing, the use of non-NetFx task-subroutines, or other traffic on the network.

4 Run–time support for task parallelism

The NetFx run–time system is responsible for efficiently transporting data sets between modules. This task is complicated by a number of requirements, including dynamic distribution and module bindings, asynchrony, the desire for compile–time customizability, and node and network heterogeneity. The interface exported by the run–time system presents the abstraction of high–level module–to–module communication of distributed data sets. Generating low level communication from the inter–module communication calls generated by compiler is in general very complex since the arrays involved may have arbitrary distributions inside modules. The run–time system uses a distribution management library that is linked in, as well as custom distribution management functions generated by the compiler and registered with the run–time system. This customizing mechanism also provides a path for extending the range of supported distribution types and supporting external non Fx routines.

In this section, we first explain what is involved in inter–module communication, defining the terms we will use along the way. Next, we describe the interface exported by the run–time system. This is followed by an explanation of the run–time system's internal structure and interfaces. Finally, we show how the interfaces are traversed during the execution of a simple send operation.

4.1 Inter–module communication

The goal of NetFx inter–module communication is to transport a data set from a source module to a destination module. The elements of the data set are partitioned across the processes of a module according to some rule. This rule is identified by the data set's distribution type and distribution. A *distribution type* identifies a class of similar rules, while a *distribution* identifies a specific member of the class. For example, the distribution type of *HPF_ARRAY* includes the distribution $(*, BLOCK)$. In NetFx, the distribution type of the data set on each module is constant throughout the execution of the program, however its distribution may change. If the distribution can change, we say that its *binding* is *dynamic*, otherwise it is *static*. The initial value of both kinds of bindings are supplied at compile time.

To send the data set from a source module to a destination module, it is necessary to be able to translate between the distributions at the two end–points. It is only possible to translate between distributions whose global structures are compatible. For example, if the source global structure is an array, then the destination global structure must be an array of the same size and shape. The end–point distribution types identify a method for translating between the two member distributions, a process called *distribution computation*. Given two distributions of the appropriate type and a process pair, the method, or *distribution function*, returns an *offset relation* between offsets into the chunk of elements owned by each process. This architecture–independent relation can be trivially converted to an architecture–dependent *address relation*, which maps memory addresses on one machine to memory addresses on the other.

The distribution functions operates under the abstraction that a data set's elements are distributed over a consecutively numbered group of processes of the module. Once an address relation has been computed for each pair of processes, the abstract process numbers must be mapped to the actual nodes of the machines on the network. The properties of these module bindings are similar to those of the distribution bindings discussed above. Specifically, the bindings may be static or dynamic. Once the mappings are known, actual data transfer can begin.

4.2 Interface

The NetFx compiler generates calls to the run–time system, which in turn may call custom distribution management functions generated by the compiler. The interface between the NetFx executable and the run–time system has three components as shown in Figure 4. The first two of these are exported by the run–time system, while the last is exported by the NetFx program itself. The first component is the *inter–module communication interface*, which consists of simple, high–level, non–blocking collective send and receive calls for transporting whole distributed data sets between modules. It is required that if more than one data set is transferred between a pair of modules, the order of the sends and receives on the modules be the same. The arguments of the send and receive calls are

- Target (send) or source (receive) module
- Address of first element local to the the calling process
- Data type of each element
- Sender distribution type and distribution
- Receiver distribution type and distribution
- Hint (implementation specific)

There is a single call to wait for all outstanding receives to complete which allows a module to complete input communication before executing.

Before performing sends and receives, the NetFx program must describe the characteristics of relevant modules, distribution types, and custom distribution functions to the run–time system. This is done through the *registry interface*. The NetFx program explicitly registers the initial module mapping and whether it is static or dynamic. Registry of distribution type is required if the distribution type is not library-supported, or if the distribution is dynamic. Dynamic bindings are updated implicitly by examining send and receive calls. There are several reasons why a program may want to register its own distribution types. One reason is extensibility — the distribution type may not be supported by the library. Another is efficiency — the compiler may have been able to generate a specialized distribution function for a particular communication. In either case, the program must also register custom distribution functions for any communication that involves the new distribution type. For example, suppose module 1 communicates from a new distribution type *DTX* to predefined types *DT*2 on module

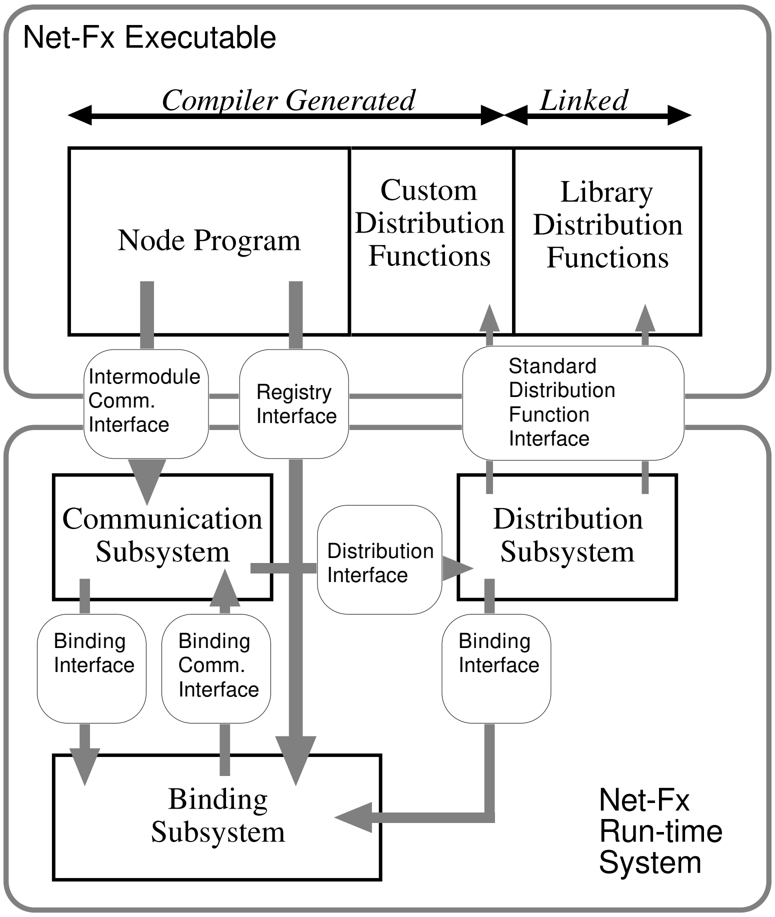


Figure 4: The NetFx run–time system: subsystems, interfaces, and relation to the NetFx executable

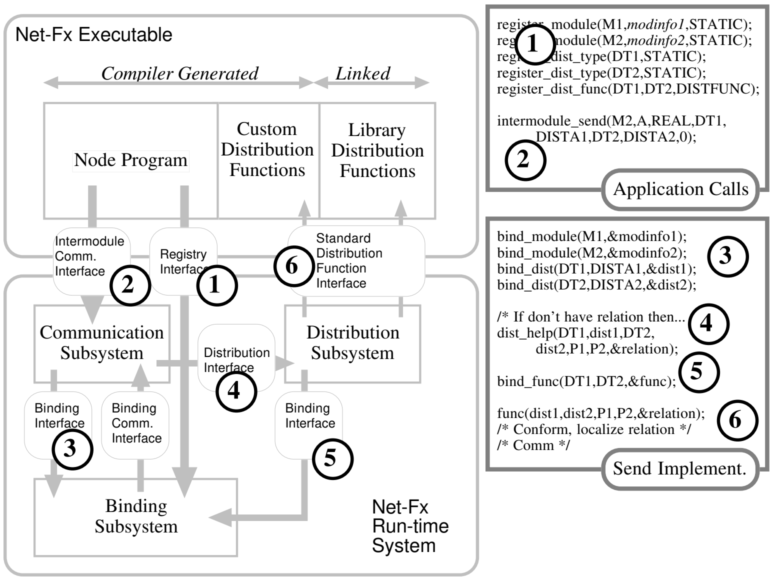
2 and $DT3$ on module 3. All three modules must register distribution type DTX. Module 1 must register new distribution functions $\lambda(DTX, DT2)$ and $\lambda(DTX, DT3)$, module 2 must register $\lambda(DTX, DT2)$, and module 3 must register $\lambda(DTX, DT3)$.

All distribution functions must conform to a common calling convention, the *standard distribution function interface*, which is the third component of the interface between the NetFx program and the run-time system. Each distribution function must be able to both return offset relations or assemble/disassemble message buffers. The run–time system decides which functionality is used.

4.3 Internal structure

The run–time system presents the abstraction of "module–to–module" communication of a distributed data set between uniquely labeled modules. This requires distribution computation, binding maintenance, and efficient communication over heterogeneous networks. These tasks are segregated into three subsystems (distribution, binding, and communication) with well defined interfaces between them. More than just good design practice, the ability to independently develop and enhance each subsystem is vital for extensibility and good performance. Clearly, the number of distribution types will grow as NetFx is used to coordinate non–Fx modules. Further, compile–time optimization of distribution computation is important for performance [8]. There are a variety of mechanisms that could be used to support dynamic bindings and it is unclear that any one is best for all environments. Finally, to achieve high performance, it will be necessary to specialize the communication system for different networks. By clearly defining the interfaces between subsystems, we make this specialization possible and easy. Indeed, all the subsystems are "plug–and–play."

The internals of the run–time system are shown in Figure 4. The *communication subsystem* is the heart of



```
register_module(M1,modinfo1,STATIC);
register_module(M2,modinfo2,STATIC);
register_dist_type(DT1,STATIC);
register_dist_type(DT2,STATIC);
register_dist_func(DT1,DT2,DISTFUNC);

intermodule_send(M2,A,REAL,DT1,
        DISTA1,DT2,DISTA2,0);
```

```
bind_module(M1,&modinfo1);
bind_module(M2,&modinfo2);
bind_dist(DT1,DISTA1,&dist1);
bind_dist(DT2,DISTA2,&dist2);

/* If don't have relation then...
dist_help(DT1,dist1,DT2,
        dist2,P1,P2,&relation);

bind_func(DT1,DT2,&func);

func(dist1,dist2,P1,P2,&relation);
/* Conform, localize relation */
/* Comm */
```

Figure 5: Example of the steps followed for an inter–module send using a custom distribution function.

the run–time system and exports the previously discussed inter–module communication interface to the NetFx program. It makes use of the *binding subsystem* to determine the current module and distribution bindings. In return it supplies the binding subsystem with a simple *binding communication interface* in case the binding system needs to perform an inter–module communication step to to determine a binding (for example, the distribution of an irregular data structure). To translate between the source and target distributions, the communication subsystem calls on the *distribution subsystem* via the *distribution interface*. This subsystem serves two purposes. First, it dispatches the appropriate distribution function for the sender and receiver distribution types. Second, it conforms the offset relation returned by that function to the format desired by the communication system and converts it to an address relation. (The communication system can request that a message be assembled or disassembled instead.) The subsystem uses the binding interface to bind the two distribution types to the distribution function. This function may be one of the *library distribution functions* linked to every NetFx executable, or a compiler–generated *custom distribution function*.

Once address relations have been computed (or messages assembled), the communication system can use the module bindings to identify the actual nodes to communicate with and perform the actual data transfer in a network and architecture dependent manner.

4.4 Example

We illustrate how an inter–module send using a custom distribution function is performed. Figure 5 shows the steps graphically. On the right are the actual calls performed by the node program and those performed internally for the inter–module send. The calls are numbered to correspond to the interfaces used and to the steps discussed in this section. There is a dependence from module $M1$ to module $M2$ and the compiler has generated a send from $M1$ to $M2$ (and a matching receive in $M2$, which is not discussed here.) The compiler also produced a custom distribution function *DISTFUNC* for this communication. At run time, $M1$'s first step is to use the registry interface to register the initial values of all relevant bindings. The module bindings for $M1$ and $M2$ are registered as static, as are the distribution types $DT1$ and $DT2$. Finally, $M1$ registers *DISTFUNC* as the distribution function for $DT1$ and $DT2$.

The second step (which may be repeated many times) is to invoke a send of the distributed data set A to $M2$. The inter–module send call includes the target module number, $M2$, the first element of A that is local to the process, the data type of A's elements (REAL), the sender and receiver distribution types, $DT1$ and $DT2$, and the current sender and receiver distributions, $DISTA1$ and $DISTA2$. The third step is to bind the two modules to their current physical mappings, and the distribution types and distributions to their current distributions. Both of these steps are simple in this case because the bindings are static — they amount to local lookups. In the fourth step, the communication subsystem calls the distribution subsystem to build an address relation between each pair of sender and receiver processes $P1$ and $P2$. The distribution subsystem accomplishes this by binding the two distribution types, $DT1$ and $DT2$, to their corresponding distribution function, *DISTFUNC* (step 5) and calling the function for each pair (step 6). The offset relations returned are conformed to the format the communication subsystem wanted and converted to address relations. Finally, the relations are used to perform the actual communication in a environment–dependent manner. The communication subsystem may decide to keep the address relations handy to avoid steps 4–6 the next time the inter–module send occurs.

5 Status and implementation

The Fx compiler currently supports task parallelism on the Intel iWarp, Intel Paragon, and on DEC Alpha workstations running PVM. Compiler analysis of parallel sections (although not mapping directive support or code emission) is the same for each target. The run–time system used on the Paragon and the Alphas was initially developed for the Alphas with an eye towards portability and serves as a prototype for the system discussed above. The prototype essentially has three components: a component that computes offset relations for any two (static) HPF distributions, a component that conforms these relations to a particular format and caches them, and a component that does communication using the relations. Porting this run–time system to the Paragon (and achieving good performance) required rewriting only the communication component. Further details of the library are available in [3].

The main target network for NetFx is Gigabit Nectar [1] developed at Carnegie Mellon. A variety of communication interfaces have been developed for Nectar and we are incorporating them in NetFx. Currently we are able to execute homogeneous Fx programs across Alpha workstations using Nectar and a full heterogeneous communication interface is under development.

6 Related work

High level run–time support for communicating data parallel tasks is a fairly new research area. We compare our approach to two other run–time libraries that support communicating data parallel tasks. Opus [5] supports communication between tasks using *shared data abstractions* (SDAs). An SDA is essentially an independent object class whose private data is distributed over some set of threads and whose methods are protected with monitor semantics. For example, one could define a queue SDA whose elements are block–distributed vectors. To send a vector to another task, it is first sent to an SDA queue object (which requires a distribution computation) using the enqueue method. The receiving task would invoke the dequeue method which would cause the SDA queue object to send a data set (again requiring a distribution computation). SDAs can support many more tasking paradigms than our scheme, but appears to significantly increase the communication volume and result in unnecessary synchronization between tasks due to monitor semantics.

Closer to our scheme is the library described in [2]. This library supports communication between data parallel tasks with collective sends and receives. Sends (and receives) are split between an initialization step which performs distribution computation and builds communication schedules, and an execution step that actually performs the send. Initializations synchronize sending and receiving tasks, but can be amortized over many executions. Only static module bindings and static HPF distributions are supported. All distribution computation is done with general purpose library routines.

7 Summary and conclusions

We address programming support for high performance networks which are emerging as an increasingly important form of parallel computing. We have presented NetFx, a compiler system that supports network parallel computing. The NetFx programming model is based on integrated support for task and data parallelism originally developed for the Fx compiler system. NetFx run–time system presents a simple abstraction for module-to-module transfer of distributed data sets so that the compiler does not have to deal with the dynamic nature of the network computing environment. The run–time system allows the compiler and other tools that generate foreign data parallel modules to customize execution behavior. A clean interface between the compiler and the run–time system also allows independent development and retargetting of both. We believe that NetFx is the first tool to provide practical programming support for networks and will make network computing easier for non-specialists.

References

[1] ARNOULD, E. A., BITZ, F. J., COOPER, E. C., KUNG, H. T., SANSOM, R. D., AND STEENKISTE, P. A. The design of nectar: A network backplane for heterogeneous multicomputers. In *Proceedings of the Third International Conference on Architecutural Support for Programming Languages and Operating Systems* (Apr. 1989), ACM.

[2] AVALINI, B., CHOUDHARY, A., FOSTER, I., KRISHNAIYER, R., AND XU, M. A data transfer library for communicating data–parallel tasks. Case center tech report, Syracuse University, December 1995. To Appear.

[3] DINDA, P. A., AND O'HALLARON, D. R. The impact of address relation caching on the performance of deposit model communication. In *Third Workshop on Languages, Compilers, and Run-Time Systems for Scalable Computers* (1995). To appear.

[4] GROSS, T., O'HALLARON, D., AND SUBHLOK, J. Task parallelism in a High Performance Fortran framework. *IEEE Parallel & Distributed Technology*, 3 (1994), 16–26.

[5] HAINES, M., HES, B., MEHROTRA, P., AND ROSENDALE, J. V. Runtime support for data parallel tasks. In *Fifth Symposium on the Frontiers of Massively Parallel Computation* (1995).

[6] HIGH PERFORMANCE FORTRAN FORUM. *High Performance Fortran Language Specification, Version 1.0*, May 1993.

[7] MCRAE, G., RUSSELL, A., AND HARLEY, R. *CIT Photochemical Airshed Model - Systems Manual*. Carnegie Mellon University, Pittsburgh, PA, and California Institute of Technology, Pasadena, CA, Feb. 1992.

[8] STICHNOTH, J., O'HALLARON, D., AND GROSS, T. Generating communication for array statements: Design, implementation, and evaluation. *Journal of Parallel and Distributed Computing 21*, 1 (1994), 150–159.

[9] SUBHLOK, J., O'HALLARON, D., GROSS, T., DINDA, P., AND WEBB, J. Communication and memory requirements as the basis for mapping task and data parallel programs. In *Supercomputing '94* (Washington, DC, November 1994), pp. 330–339.

[10] SUBHLOK, J., STICHNOTH, J., O'HALLARON, D., AND GROSS, T. Exploiting task and data parallelism on a multicomputer. In *ACM SIGPLAN Symposium on Principles and Practice of Parallel Programming* (San Diego, CA, May 1993), pp. 13–22.

[11] SUBHLOK, J., AND VONDRAN, G. Optimal mapping of sequences of data parallel tasks. In *Proceedings of the Fifth ACM SIGPLAN Symposium on Principles and Practice of Parallel Programming* (Santa Barbara, CA, July 1995). To appear.

[12] YANG, B., WEBB, J., STICHNOTH, J., O'HALLARON, D., AND GROSS, T. Do&merge: Integrating parallel loops and reductions. In *Sixth Annual Workshop on Languages and Compilers for Parallel Computing* (Portland, Oregon, Aug 1993).