Compositional Development of Parallel Programs

Nasim Mahmood, Guosheng Deng, and James C. Browne

UTCS

Department of Computer Sciences

The University of Texas at Austin

Overview

- Motivation
- Goals
- Programming Model
- Example
- Case Study
- Conclusions
- Current and Ongoing Work
- Future Directions

Motivation

- Optimization and adaptation of parallel programs is effort intensive
  - Different execution environments
  - Different problem instances
- Direct modification of complete application is effort intensive
- Maintenance and evolution of parallel programs is a complex task

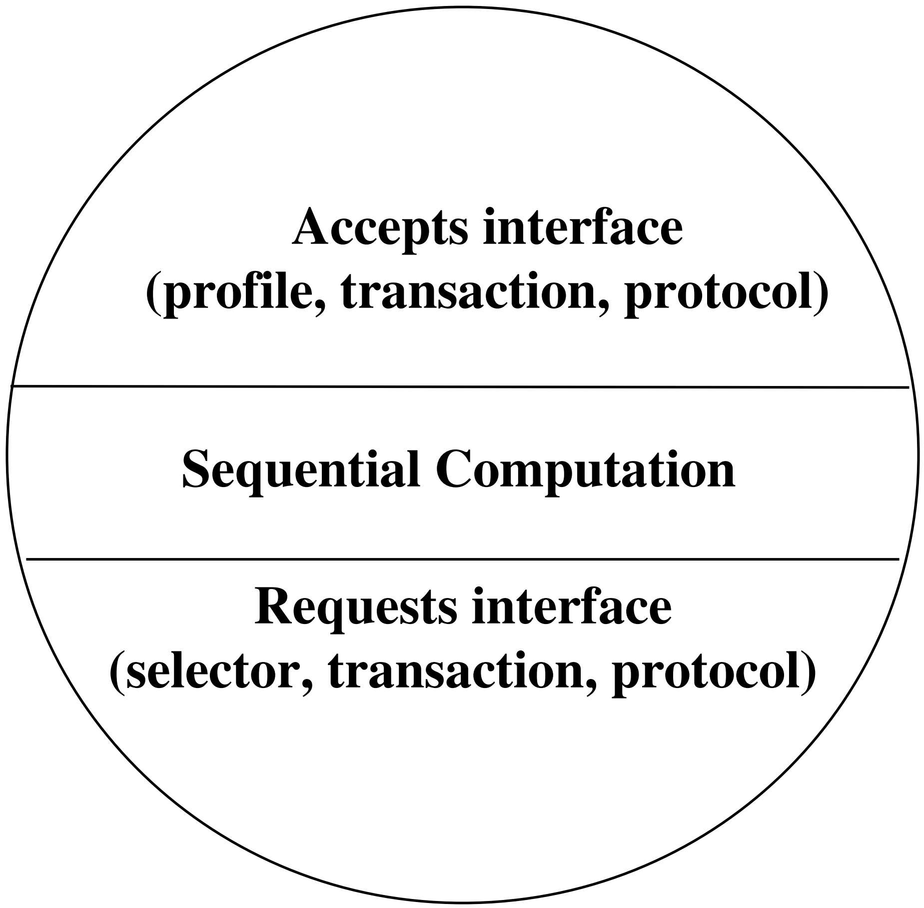
Goals

- Order of magnitude productivity enhancement for program families
  - Develop parallel programs from sequential components
  - Reuse components
  - Enable development of program families from multiple versions of components
  - Automatic composition of parallel programs from components

Programming Model

- Component Development
  - Domain Analysis
  - Component Development
  - Encapsulate
- Program Instance Development
  - Analyze problem instance and execution environment
  - Identify attributes and attribute values
  - Identify data flow graph
  - Specify the program using the components and their interfaces

Component



Accepts interface
(profile, transaction, protocol)
Sequential Computation
Requests interface
(selector, transaction, protocol)

2D FFT Example

- Steps for 2D FFT computation
  - Partition given matrix row-wise
  - Apply 1D FFT to each row of the partition
  - Combine the partitions and transpose the matrix
  - Partition transposed matrix row-wise
  - Apply 1D FFT to each row of the partition
  - Combine the partitions and transpose the matrix
  - Transposed matrix is the 2D FFT of the original matrix

2D FFT Example (Cont'd)

Fft_row
a) Domain: fft
b) Input: matrix
c) Element_type: complex
d) Algorithm: 1d-fft
e) Apply_per_row: true

Gather_transpose
a) Domain: matrix
b) Function: gather
c) Element_type: complex
d) Combine_by_row: true
e) Transpose: true

Distribute
a) Domain: matrix
b) Function: distribute
c) Element_type: complex
d) Distribute_by_row: true

Print
a) Domain: print
b) Input: matrix
c) Element_type: complex

Fig. 2. Domain Analysis of the Components

2D FFT Example (Cont'd)

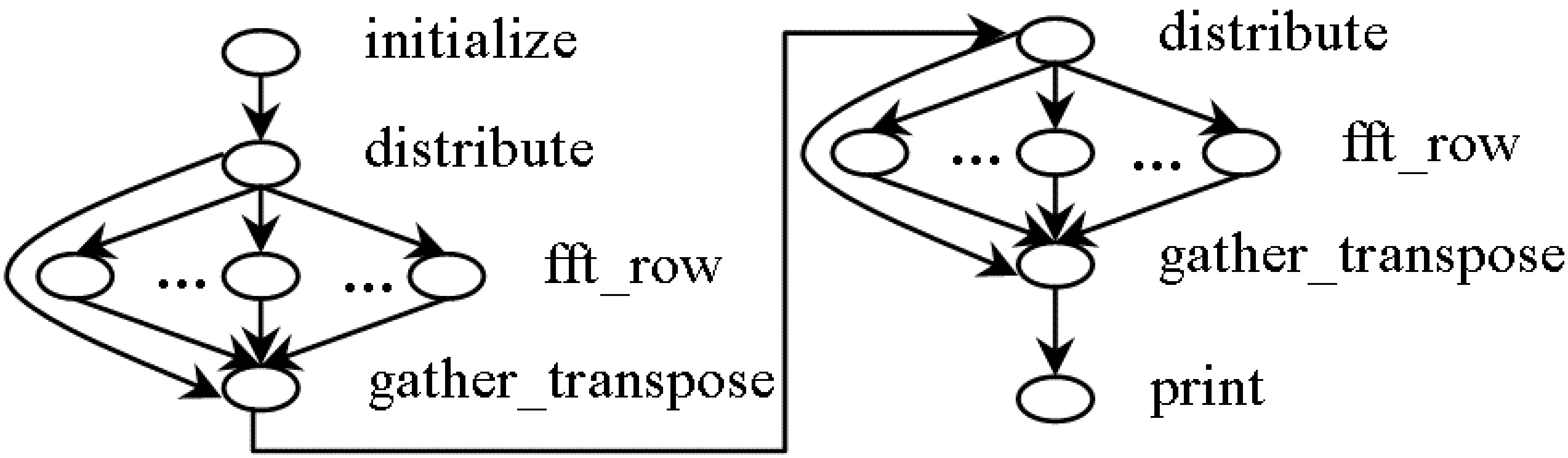


Fig. 1. Data Flow Graph of 2D FFT Computation

2D FFT Example (Cont'd)

```
selector:
  string domain == "matrix";
  string function == "distribute";
  string element_type == "complex";
  bool distribute_by_row == true;
transaction:
  int distribute(out mat2 grid_re,out mat2 grid_im, out int n,
                 out int m, out int p);
protocol: dataflow;
```

Requests interface of Initialize

```
profile:
  string domain = "matrix";
  string function = "distribute";
  string element_type = "complex";
  bool distribute_by_row = true;
transaction:
  int distribute(in mat2 grid_re,in mat2 grid_im, in int n,
                 in int m, in int p);
protocol: dataflow;
```

Accepts interface of Distribute

Compilation Process

- Matching of
  - Selector and profile
  - Transactions
  - Profiles
- Matching starts from the selector of the start component
- Applied recursively to each matched components
- Output is a generalized data flow graph as defined in CODE (Newton '92)
- Data flow graph is compiled to a parallel program for a specific architecture

2D FFT Example (Cont'd)

```
{selector:
  string domain == "fft";
  string input == "matrix";
  string element_type == "complex";
  string algorithm == "Cooley-Tukey";
  bool apply_per_row == true;
transaction:
  int fft_row(out mat2 out_grid_re[],out mat2
          out_grid_im[], out int n/p, out int m);
protocol: dataflow;
}index [ p ]
```

Requests interface (partial) of Distribute

```
profile:
  string domain = "fft";
  string input = "matrix";
  string element_type = "complex";
  string algorithm = "Cooley-Tukey";
  bool apply_per_row = true;
transaction :
  int fft_row(in mat2 grid_re,in mat2 grid_im,in int n,
                  in int m);
protocol: dataflow;
```

Accepts interface of FFT_Row

2D FFT Example (Cont'd)

```
selector:
  string domain == "matrix";
  string function == "gather";
  string element_type == "complex";
  bool combine_by_row == true;
  bool transpose == true;
transaction:
  int gather_transpose(out mat2 out_grid_re,out mat2
                       out_grid_im, out int me);
protocol: dataflow;
profile:
  string domain = "matrix";
  string function = "gather";
  string element_type = "complex";
  bool combine_by_row = true;
  bool transpose = true;
transaction:
  int get_no_of_p(in int n, in int m, in int p,in int state);
   >
  int gather_transpose(in mat2 grid_re,in mat2 grid_im,
                       in int inst);
protocol: dataflow;
```

Requests interface of FFT_Row

Accepts interface of Gather_Transpose

2D FFT Example (Cont'd)

```
selector:
  string domain == "matrix";
  string function == "distribute";
  string element_type == "complex";
  bool distribute_by_row == true;
transaction:
  %{ exec_no == 1 && gathered == p }%
  int distribute(out mat2 out_grid_re,out mat2
                out_grid_im, out int m, out int n*p,
                out int p);
protocol: dataflow;
```

Requests interface (partial) of Gather_Transpose

Fast Multipole in Short

- Compute the Coulomb Energy of point charges in linear time
- Transforming the information about a cluster of charge into a simpler representation which is used to compute the influence of the cluster on objects at large distances by scaling all particles into hierarchy of cubes in different levels
- Can be extended and applied to astrophysics, plasma physics, molecular dynamics, fluid dynamics, partial differential equations and numerical complex analysis

Generalized Fast Multipole Solver – Matrix Version

- Many generalized *N*-body problems can be treated as multiple FMM problems which share the same geometry. This feature can be exploited by combining the generalized charges into a vector

- Generalized FMM is an extension of the FMM algorithm to multiple “charge types”

- More efficient FMM translation routines could be built using BLAS routines

FMM Domain Analysis

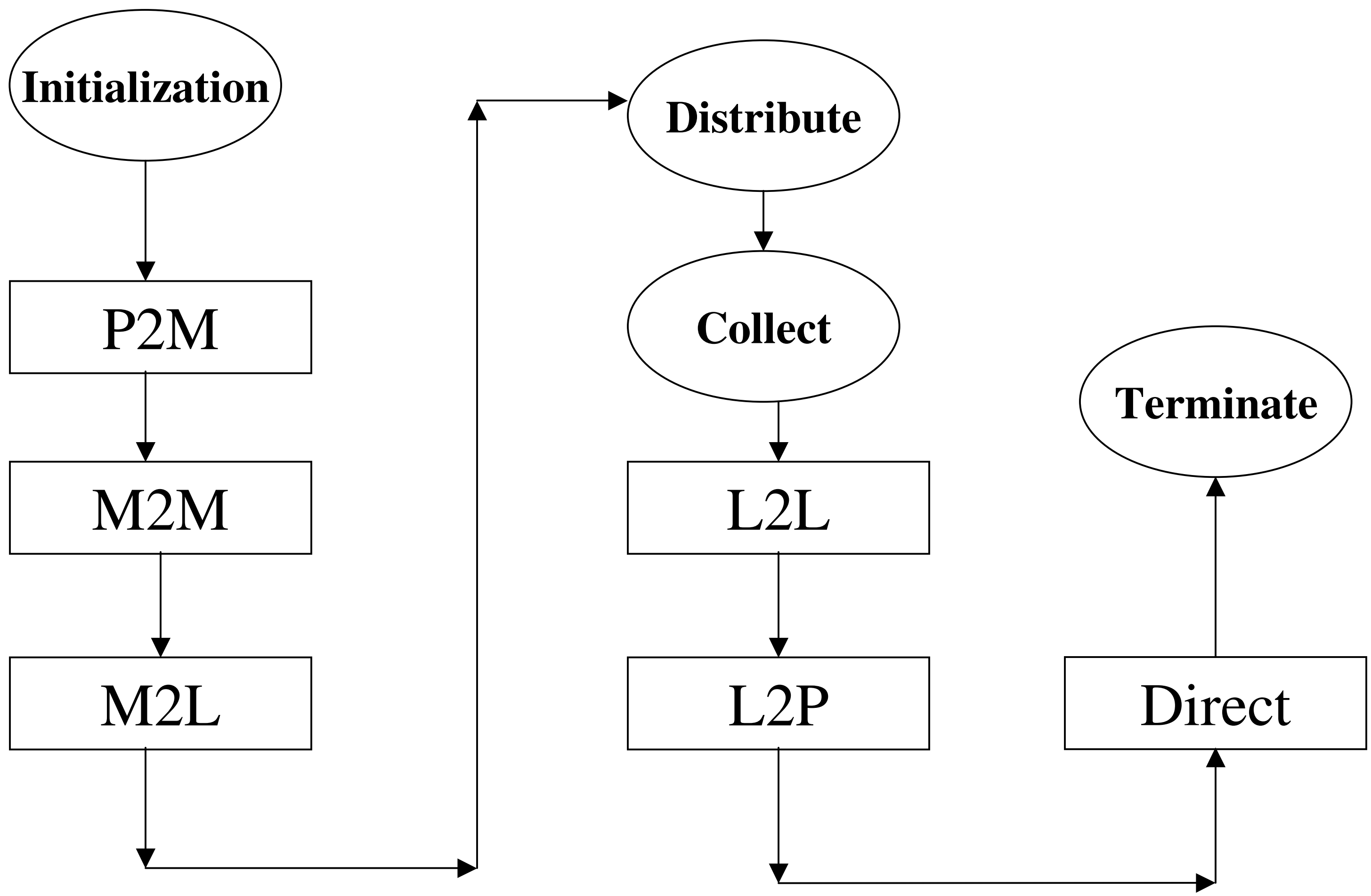
- Six Translation Components
  - Particle charge to Multipole (finest partitioning level)
  - Multipole to Multipole (between all partitioning levels, from the finest to the coarsest)
  - Multipole to Local (all partitioning levels)
  - Local to Local (between all partitioning levels)
  - Local to Particle potential and forces (finest partitioning level)
  - Direct Interaction (finest partitioning level)

- Two Utility Components
  - Distribute – Distribute Pre-Calculated Local Coefficient matrices according to Interaction list
  - Gather – Gather Local coefficients

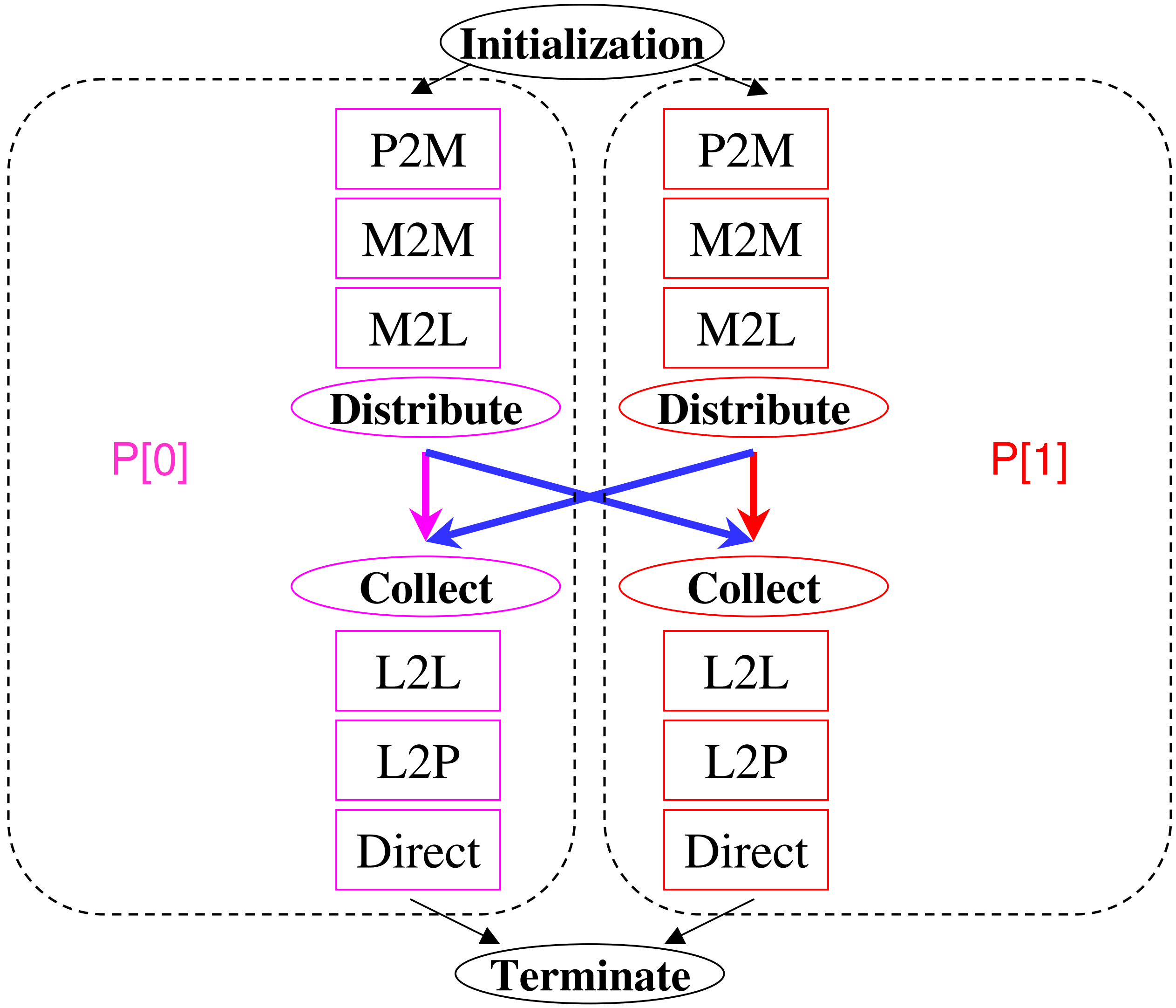
Space-computation Tradeoffs For Matrix-structured Formulation of the FMM Algorithm

- Simultaneous computation of cell potentials for multiple charge types
- Use of optimized library routines for vector-matrix and matrix-matrix multiply
- Loop interchange over the two outer loops to improve locality

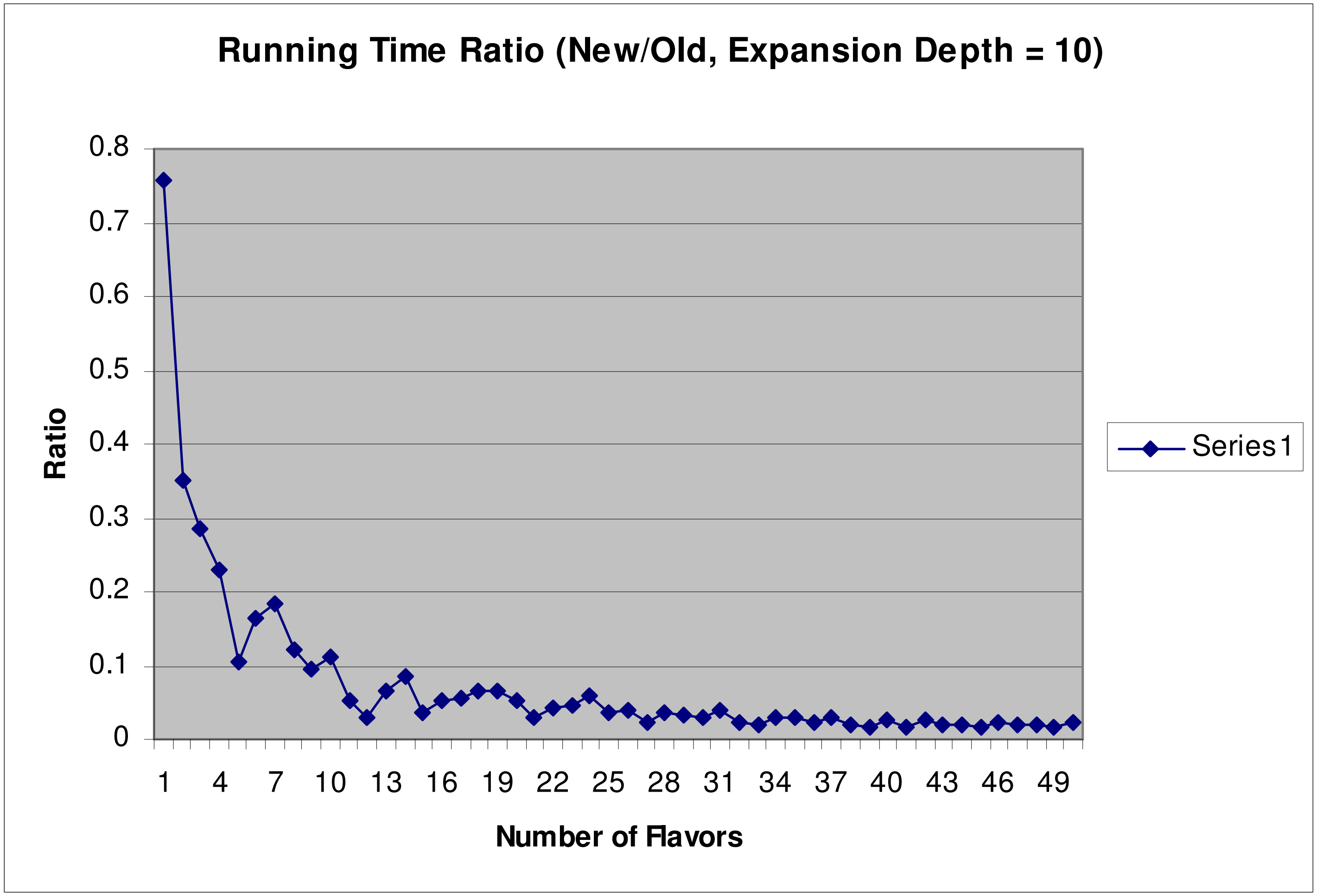
Flow Graph for Sequential FMM



Flow Graph for The Parallel Version



Sequential Running Time - New/Old WRT number of charge types



Conclusions

- Effort in domain analysis is not trivial
- Suitable for
  - Large applications that are to be optimized for several different execution environments
  - Large applications that are expected to evolve over a substantial period of time
  - Large applications with multiple instances
- Competitive program performance

Current and Ongoing Work

- Implement evolutionary performance models of programs through composition of components
  - Abstract components
  - Concrete components
  - Performance model for specific architecture
- Componentize hp-adaptive finite element code and Method of Lines (MOL) code

Future Directions

- Combine with dynamic linking runtime system based on associative interfaces [Kane '02]
- Implement more powerful precedence and sequencing operators for state machine specifications
- Integrate with Broadway [Guyer/Lin '99] annotational compiler to overcome "many components" problem