Charm++: Migratable Objects + Active Messages + Adaptive Runtime = Productivity + Performance

Laxmikant V. Kale, Anshu Arya, Nikhil Jain, Akhil Langer, Jonathan Lifflander, Harshitha Menon, Xiang Ni, Yanhua Sun, Ehsan Totoni, Ramprasad Venkataraman, Lukasz Wesolowski

Charm++ is an elegant, general-purpose parallel programming model backed by an adaptive runtime system. This combination yields portable performance and a spectrum of real-world productivity benefits that have been demonstrated in production applications. A Charm++-based benchmark suite was submitted to HPC Challenge competition (which is aimed at comparing productivity); in 2011 we were co-winners, in 2012, we were finalists.

Productivity						Performance		
Code	C++	CI	Benchmark Subtotal	Driver	Total	Machine	Max Cores	Performance Highlight
Required Benchmarks								
1D FFT	54	29	83	102	185	BG/P BG/Q	64K 16K	2.71 TFlop/s 2.31 TFlop/s
Random Access	76	15	91	47	138	BG/P BG/Q	128K 16K	43.10 GUPS 15.00 GUPS
Dense LU	1001	316	1317	453	1770	XT5	8K	55.1 TFlop/s (65.7% peak)
Additional Benchmarks								
Molecular Dynamics	571	122	693	n/a	693	BG/P BG/Q	128K 16K	24 ms/step (2.8M atoms) 44 ms/step (2.8M atoms)
AMR	1126	118	1244	n/a	1244	BG/Q	32k	22 steps/sec, 2d mesh, max 15 levels refinement
Triangular Solver	642	50	692	56	748	BG/P	512	48x speedup on 64 cores with helm2d03 matrix

Salient Features

Object-based

Parallel programs in Charm++ are implemented in an object-based paradigm. Computations are expressed in terms of work and data units that are natural to the algorithm being implemented and not in terms of physical cores or processes executing in a parallel context. This immediately has productivity benefits as application programmers can now think in terms that are native to their domains.

The work and data units in a program are C++ objects, and hence, the program design can exploit all the benefits of object-oriented software architecture. Classes that participate in the expression of parallel control flow (*chares*) inherit from base classes supplied by the programming framework.

Chares are typically organized into indexed collections, known as *chare arrays*. Chares in an array share a type, and hence present a common interface of *entry methods*.

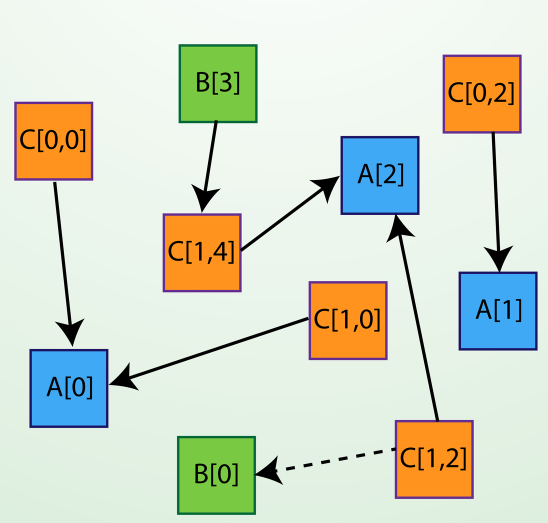
Runtime-assisted

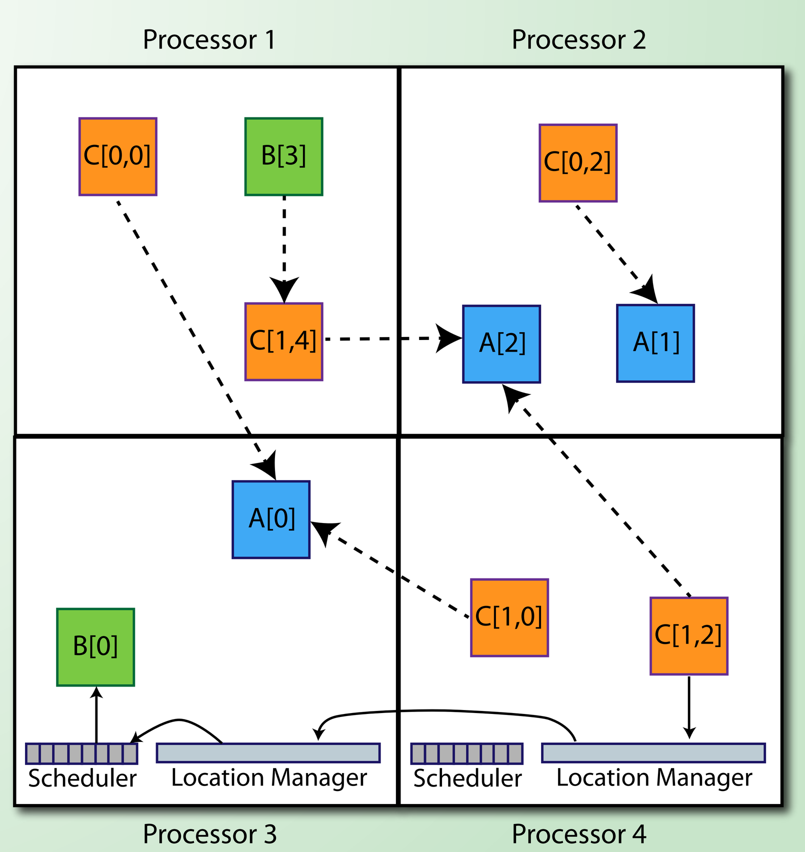
Once an application has been expressed as a set of overdecomposed message-driven objects, these can be mapped onto the available compute resources and their executions managed by a runtime system. The programming model permits an execution model where the run-time system can:

- maintain a queue of incoming messages, and deliver them to entry methods on local chares.
- overlap data movement required by a chare with entry method executions for other chares.
- observe computation / communication patterns, and move chares to balance load and optimize communi- cation.
- allow run-time composition (interleaving) of work from different parallel modules.

Message-Driven

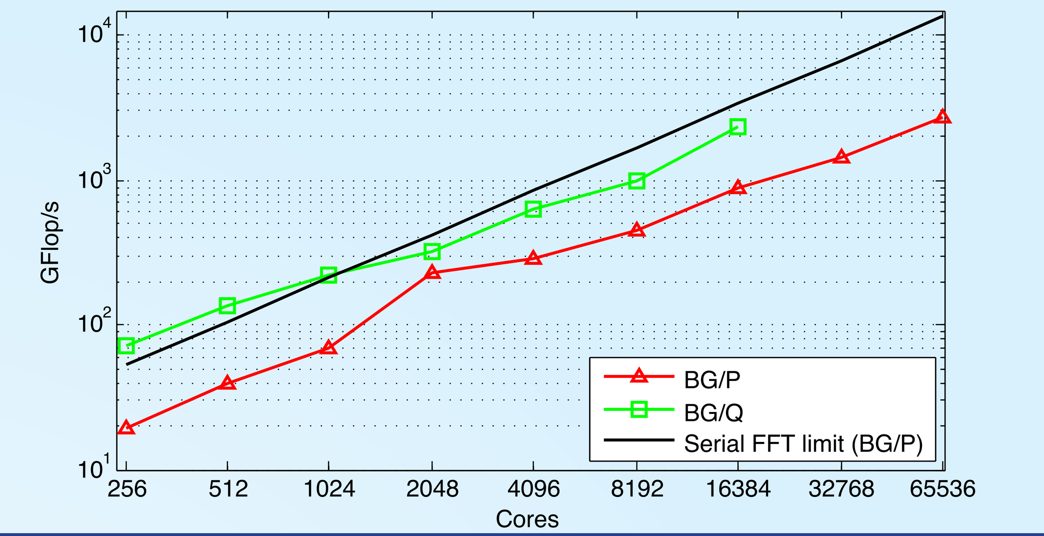
Messaging in Charm++ is sender-driven and asynchronous. Parallel control flow in Charm++ is expressed in the form of method invocations on remote objects. Each chare simply uses its entry methods to describe its reactions when dependencies (remote events or receipt of remote data) are fulfilled. Once this happens, it can perform appropriate computations and also trigger other events whose dependencies are now fulfilled. The parallel program then becomes a collection of objects that trigger each other via remote (or local) invocations by sending messages.





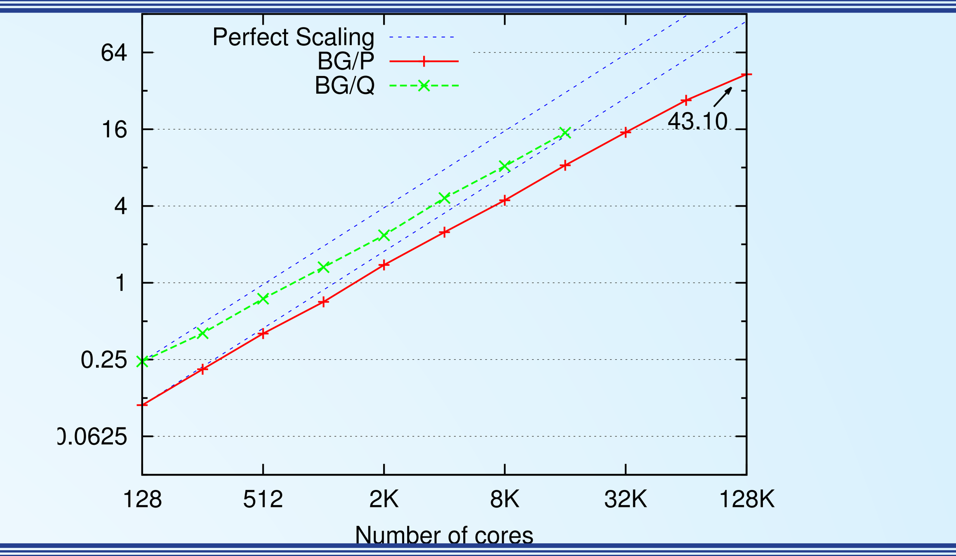
1D FFT

Our implementation of FFT performs a complex 1D FFT on an NxN matrix where subsequent rows are contiguous elements of a complex vector. Three all-to-all transposes are required to perform the FFT and unscramble the data. All-to-all operations are done via a general Charm software routing library, Mesh Streamer, and external libraries (FFTW or ESSL) perform serial FFTs on the rows of the matrix.



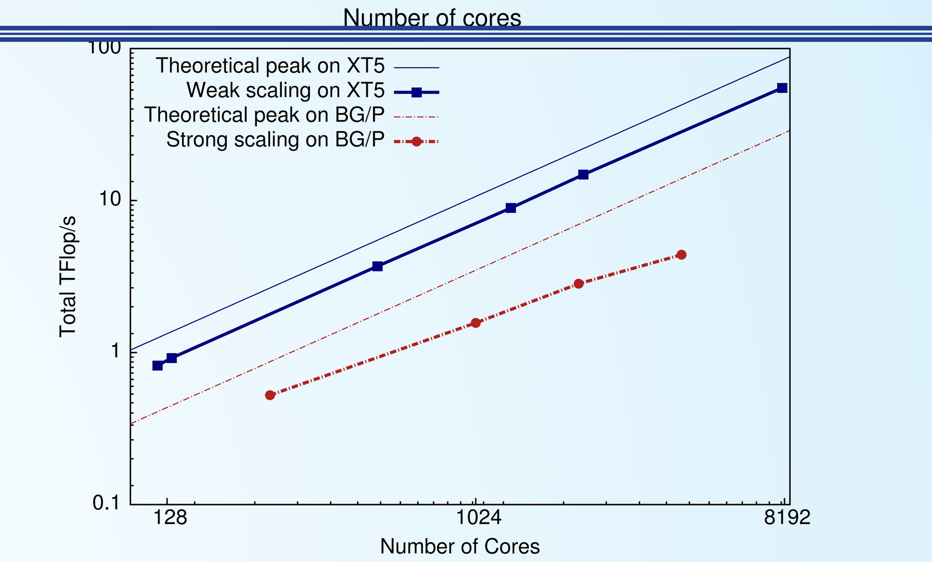
Random Access

The global table is partitioned across the nodes in the run.Each element of the group allocates its part of the global table, generates random update keys, and sends the updates to the appropriate destination. The Charm++ Mesh Streamer library automates aggregation and routing, based on network topology information provided by Charm++ Topoology Manager.



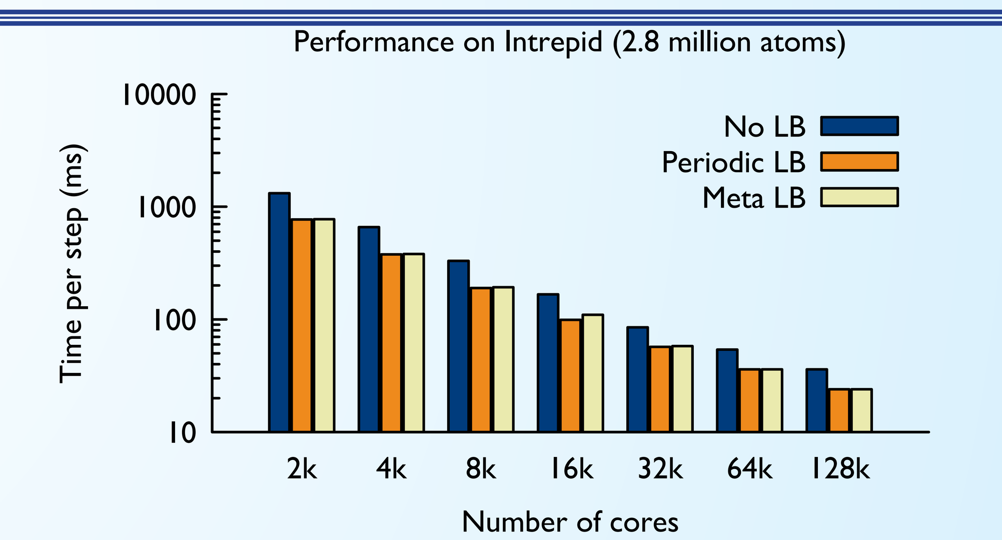
Dense LU

Our implementation provides dynamic, memory-constrained lookahead so that panel factorizations are overlapped as much as memory usage limits will allow. The placement of matrix blocks on processes is independent of the main factorization routines; it is encapsulated in a sequential function. We use asynchronous collectives for pivot identification reductions so they can be overlapped with updating the rest of the sub-panel.



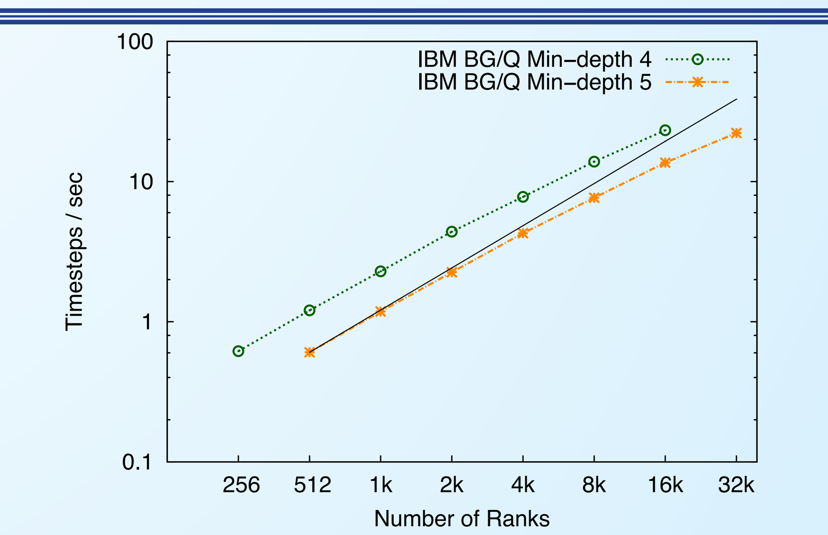
Molecular Dynamics

LeanMD simulates the behavior of atoms based on the Lennard-Jones potential, which mimics the short-range non-bonded force calculation in NAMD and resembles miniMD in the Mantevo suite. Charm++'s fully automated load balancing enables exceptional strong scaling. To enable automatic load balancing decisions, the user simply specifies a flag, +MetaLB, and the run-time system automatically identifies a load balancing period.



AMR

In our implementation, blocks are first-class entities that in a collection that expands and contracts as the mesh is refined or coarsened, without requiring synchronization. Refinement decisions are local to each block and propagated as far as algorithmically required. We use scalable termination detection built into our runtime to globally determine when all refinement decisions have been finalized, reducing many overheads.



Sparse Triangular Solver

The matrix is divided into blocks of columns then analyzed to find its independent rows for computation. Dense regions below the diagonal section are divided into new blocks. Each diagonal block starts the computation with its independent parts and waits for required messages from the left. The column blocks are mapped round-robin, which is essential for this solver and managing the blocks manually is burdensome for the programmer.