Neutron Star Evolutions using Tabulated Equations of State with a New Execution Model

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Abstract—The addition of nuclear and neutrino physics to general relativistic fluid codes allows for a more realistic description of hot nuclear matter in neutron star and black hole systems. This additional microphysics requires that each processor have access to large tables of data, such as equations of state, and in large simulations the memory required to store these tables locally can become excessive unless an alternative execution model is used. In this work we present relativistic fluid evolutions of a neutron star obtained using a message driven multi-threaded execution model known as ParalleX. These neutron star simulations would require substantial memory overhead dedicated entirely to the equation of state table if using a more traditional execution model. We introduce a ParalleX component based on Futures for accessing large tables of data, including out-of-core sized tables, which does not require substantial memory overhead and effectively hides any increased network latency.

Index Terms—Astrophysics applications, ParalleX, HPX, Futures

I. INTRODUCTION

Future achievements in leading-edge science demand innovations in parallel computing models and methods to improve efficiency and dramatically increase scalability. One controversial issue is the relative value of global address space models and management versus more conventional distributed memory structure. This paper demonstrates one important use of global address space in the context of the advanced ParalleX execution model that has enabled simulation improvements to be achieved in the domain of astrophysics that is not feasible using conventional practices.

Accurate treatment of hot nuclear matter in astrophysical compact object simulation is becoming increasingly important in the search for coincident detection of gravitational radiation and electromagnetic or neutrino emissions originating from the same source. Recent simulations have shown that the gravitational wave signature from a binary neutron star merger or a neutron star–black hole merger may even reveal important empirical details about the neutron star equation of state itself [1], [2].

The addition of nuclear and neutrino physics to general relativistic fluid codes allows for a more realistic description of hot nuclear matter in neutron star and black hole systems. Unfortunately, most of these and other microphysics routines cannot be computed in place; they must be precomputed in a large table which is then read and interpolated as the relativistic hydrodynamics simulation proceeds. Accurate neutron star simulations will increasingly rely upon even larger tables of microphysics data which must be read into memory, searched, and interpolated [3]. As the memory requirements grow for these tables, approaching and often exceeding the size of the physical memory of a single node, the need for an alternative to the traditional MPI-OpenMP hybrid approach is increasingly evident.

In this work we explore the experimental execution model called ParalleX [4]–[7] as a means of addressing the critical computational requirement of dealing with very large tables containing microphysics. ParalleX provides many other performance benefits to a distributed relativistic hydrodynamics simulation but the focus of this work will be on matters related to equation of state tables.

ParalleX is a synthesis of complementing semantic constructs delivering a dynamic adaptive framework for message-driven multi-threaded computing in a global address space context with constraint-based synchronization to exploit locality and manage asynchrony. The result is introspective runtime alignment of computing requirements and computing resources while permitting asynchronous operation across physically distributed resources. ParalleX has been first implemented in the form of the HPX runtime system [8], [9], developed to support the semantics and mechanisms comprising ParalleX targeting conventional SMP and commodity cluster computing platforms. This experimental software package is developed to test the semantics of ParalleX, to measure the overhead costs of software implementation, and to provide a prototype of the next generation runtime system for extreme scale applications.

The outline of this paper as follows: section II describes the relativistic fluid evolution, initial data, numerical methods, and equation of state details; section III gives a brief overview of the HPX runtime system implementation of ParalleX; section IV describes how the equation of state is distributed across nodes and how Futures are used to hide network latency.
in table access; section [V] gives neutron star evolution performance results using the Shen equation of state comparing the Futures approach of accessing the equation of state with that of reading in the table for every core (referred to hereafter as the conventional approach); section [VI] gives our conclusions and implications for future work.

II. RELATIVISTIC HYDRODYNAMICS

The work presented here adopts the flux-conservative formulation of the relativistic magnetohydrodynamics equations presented in [10] and includes high-resolution shock capturing (HRSC) methods. To calculate the numerical fluxes, we use the Piecewise Parabolic Method (PPM) [11] for reconstructing fluid variables. The approximate Riemann solver employed is Harten-Lax-van Leer-Einfeldt (HLLE) [12]. While the code is capable of also evolving magnetic fields, no magnetic fields were added to the initial data at this stage. Neutron star simulations presented in section [V] were conducted using the Cowling approximation.

The tabulated equation of state used for generating the initial neutron star and all subsequent fluid evolution is the Shen equation of state [13]. A tabulated Shen equation of state was provided by C. Ott and is available for download at [14]. The publicly available tabulated Shen equation of state used for tests here is 288 MB; however, an updated Shen equation of state has since been released [15] and we have created a table based on this update which is 5.9 GB in size. Consequently, results from both tables will be presented in the results section. The neutron star initial data was generated using the Lorene libraries [16]: the neutron star has a mass of 1.4 solar masses and radius of 15.947 km. Tables related to neutrino transport, including neutrino opacity, were not included in this work but are part of future work.

The entire relativistic magnetohydrodynamics solver has been implemented in C++ using the HPX runtime system for parallelism. The application has been modularized for future incorporation into the HPX Adaptive Mesh Refinement (AMR) toolkit although simulations for this work performed all computations in unigrid. The next section will give a brief overview of HPX and introduce the concepts crucial for asynchrony management in tabular access and parallel computation in general.

III. THE HPX RUNTIME SYSTEM

The C++ prototype runtime implementation of ParalleX is called High Performance ParalleX (HPX). A walkthrough description of the HPX architecture is found in Figure [1]. An incoming parcel (delivered over the interconnect) is received by the parcel port. One or more parcel handlers are connected to a single parcel port, optionally allowing to distinguish different parts of the system as the parcel’s final destination. An example for such different destinations is to have both normal cores and special hardware (such as a GPGPU) in the same locality (ParalleX term identifying synchronous domain of computation, such as a single compute node in a cluster). The main task of the parcel handler is to buffer incoming parcels for the action manager. The action manager decodes the parcel, which contains an action bundled with relevant operands. An action is either a global function call or a method call on a globally addressable object. The action manager creates a HPX-thread based on the encoded information.

All HPX-threads are managed by the thread manager, which schedules their execution on one of the OS-threads allocated to it. HPX threads are implemented as user level threads, which decreases the costs associated with their creation, destruction, and state updates by minimizing the number of interactions with the OS kernel. HPX creates one worker OS-thread for each available core, whose purpose is to carry out the majority of computations in an application. Several scheduling policies have been implemented for the thread manager, such as the global queue scheduler, where all cores pull their work from a single global queue, or the local queue scheduler, where each core pulls its work from a separate queue. The latter supports work stealing for better load balancing. In the local scheduler, a queue is created for each of the worker OS-threads. When a worker thread is searching for work, it first checks its own queue. If there is no work there, the OS-thread begins to steal work by searching for work in other queues, first from its own non-uniform memory access (NUMA) domain, then from cores located on different NUMA domains.

If a possibly remote action has to be executed by a HPX-thread, the action manager queries the active global address space (AGAS) to determine whether the target of the action is local or remote to the locality that the HPX-thread is running on. If the target happens to be local, a new HPX-thread is created immediately and passed to the thread manager. This thread encapsulates the work (function) and the corresponding arguments for that action. If the target is remote, the action manager creates a parcel encoding the action (i.e. the function and its arguments). This parcel is handed to the parcel handler, which makes sure that it gets sent over the interconnect, causing a new HPX-thread to be created at the target locality.

The Active Global Address Space (AGAS) provides global address resolution services that are used by the parcel port and the action manager. AGAS addresses are 128bit unique global identifiers (GIDs). AGAS maps these global identifiers to local addresses, and additionally provides symbolic mappings from strings to GIDs. The local addresses that GIDs are bound to are typed, providing a degree of protection from type errors. Any object that has been registered with a GID in AGAS is addressable from all localities in an instance of the HPX runtime. AGAS also provides a powerful reference counting system which implements transparent and automatic global garbage collection.

Lightweight Control Objects (LCOs) are the synchronisation primitives upon which HPX applications are built. LCOs provide a means of controlling parallelization and synchronization of HPX-threads. Semaphores, mutexes and condition variables [17] are all available in HPX as LCOs. Futures [18] are another type of LCO provided by HPX, and are discussed in greater detail later in this paper.

Local memory management, performance counters (a
Fig. 1. Modular structure of HPX implementation. HPX implements the supporting functionality for most of the elements needed for the ParalleX model: AGAS (active global address space), parcel port and parcel handlers, HPX-threads and thread manager, ParalleX processes, LCOs (local control objects), performance counters enabling dynamic and intrinsic system and load estimates, and the means of integrating application specific components.

generic monitoring framework), LCOs and AGAS are all implemented on top of an underlying component framework. Components are the main building blocks of remotely executable actions and can encapsulate arbitrary, possibly application specific functionality. Actions are special types which expose the functionality of a (possibly remote) function. An action can be invoked on a component instance using only its GID, which allows any locality to invoke the exposed methods of a component. In the case of the aforementioned components, the HPX runtime system implements its own functionality in terms of this component framework. Typically, any application written using HPX extends the set of existing components based on its requirements.

The relativistic hydrodynamics simulations make use of all the key features of HPX. The most crucial feature for contention and network latency hiding in tabulated equation of state access is the Future [18], [19]. The next section will describe the strategy adopted in HPX for distributing a large table and hiding network latency.

IV. USING THE SHEN EQUATION OF STATE TABLES

The Shen equation of state (EOS) tables of nuclear matter at finite temperature and density with various electron fractions within the relativistic mean field (RMF) theory are a set of three dimensional data arrays enabling high precision interpolation of 19 relevant parameters required for neutron star simulations. As noted in section II, the publicly available Shen equation of state table is relatively small in size (288 MB); however, the most recent Shen table created for the neutron star evolutions presented here is 5.9 GB in size. Results using both tables will be presented in section V. In the case of the larger table, loading the whole data set into main memory on each locality is not feasible. In conventional MPI based applications the full tables would have to be either loaded into each MPI process or a distributed partitioning scheme would have to be implemented. These options are either not viable or difficult to implement using MPI.

A. Interpolation Technique and Characteristics

The values of each of 19 variables describing the Shen EOS are contained in individual 3-D tables stored in memory in a row-major fashion. Single table data are arranged as samples of a single physical quantity computed at coordinates laying on a regularly spaced grid. The sizes of each grid vary from \(220 \times 180 \times 50\) for the smaller 288 MB set to \(440 \times 360 \times 130\) for the large, 5.9 GB set. The dimensions correspond to baryon mass density, temperature, and electron fraction, respectively.

To obtain the value of a variable at an arbitrary point within the 3-D domain, a \(2 \times 2 \times 2\) cube of double-precision floating numbers must be accessed. The result is computed using a simple tri-linear interpolation from these values. Our neutron star simulations require only 8 out 19 tabulated quantities, which helps reduce the memory pressure. However, even when using a single instance of the smaller set of tables on each node to permit the efficient sharing of table data among all cores, the aggregate size of accessed data volume...
still significantly exceeds the combined size of L3 processor caches. Furthermore, given that in each interpolation request effectively at most \(2 \times 8 = 16\) out of 64 bytes per cache line (x86 architecture) are used and the coordinate stream generated by the application is random, the performance of interpolation function is memory bound.

### B. The Overhead of Futures

Many HPX applications, including the relativistic hydrodynamics simulation detailed here, utilize Futures for ease of parallelization and synchronization. In HPX, Futures are implemented as two types of LCOs, Eager Futures and Lazy Futures, differing in the evaluation mode of produced value. In Eager Futures the computation providing the result value is triggered as soon as the Future object is instantiated, whereas for Lazy Futures it remains dormant until at least one consumer of the value references it. The neutron star simulation detailed in this paper makes extensive use of Eager Futures (we will refer to them simply as Futures for brevity). For this reason, the overheads of these constructs are a large factor in the total overhead of the HPX runtime in our code. In this subsection, we give a description of Futures, outline a performance test for measuring the overhead of Futures, and present the results of the test.

As shown in Figure 2, a Future encapsulates a delayed computation. It acts as a proxy for a result initially not known, most of the time because the computation of the result has not completed yet. The Future synchronizes the access of this value by optionally suspending HPX-threads requesting the result until the value is available. When a Future is created, it spawns a new HPX-thread (either remotely with a parcel or locally by placing it into the thread queue) which, when run, will execute the action associated with the Future. The arguments of the action are bound when the Future is created. Once the action has finished executing, a write operation is performed on the Future. The write operation marks the Future as completed, and optionally stores data returned by the action.

When the result of the delayed computation is needed, a read operation is performed on the Future. If the Future’s action hasn’t completed when a read operation is performed on it, the reader HPX-thread is suspended until the Future is ready.

Our benchmark for Future overhead created a fixed number of Futures, each of which had a fixed workload. Then asynchronous read operations were performed on the Futures until all of the Futures had completed. A high resolution timer measured the wall-time of the aforementioned operations. The test was run on an 8-socket HP ProLiant DL785 (each socket sports a 6-core AMD Opteron 8431) with 96 GB of RAM (533 MHz DDR2). Trials were done with varying workloads and OS-threads. Five runs were performed for each combination of the parameters and the results were averaged to produce a final dataset. The numbers are presented in Figure 3.

On the locality we used for this benchmark, the amortized overhead of a Future is approximately 17 microseconds. This overhead includes the time required to create the Future instance, start the evaluator thread, perform synchronization with the accessors, and destruct the Future object. This number was extrapolated from the data presented in Figure 3. We multiplied the workload by the number of Futures used in each run, and then subtracted that from the average wall-time of the trial. We divided that number by the number of Futures invoked in the trial to get the overhead per Future for each set of parameters.
The overhead of the distributed implementation of the Shen EOS tables, a number of tests have been performed, all of them with a fixed number of total data accesses (measuring strong scaling). The tests have been run on a different number of localities and with varying numbers of OS-threads per locality. The current HPX implementation supports only a centralized AGAS server that may be invoked in two configurations: either as a standalone task on a dedicated locality or as a part of one of the user application tasks. Our tests used a standalone AGAS server, firstly to avoid interfering with the user workload and secondly to eliminate the generation of asymmetric AGAS traffic on localities hosting data tables. Unlike the client applications, the AGAS server used a fixed number of OS-threads throughout the testing to ensure that sufficient processing resources are available to the incoming resolution requests.

The tests were performed on a small heterogeneous cluster. The cluster consists of 18 localities (excluding the head node) connected by Gigabit Ethernet network. Two of the machines are 8-socket HP ProLiant DL785s, with 6-core AMD Opteron 8431s and 96 GB of RAM (533 MHz DDR2). The other 16 localities are single-socket HP ProLiant DL120s, with Intel Xeon X3430s and 4 GB of RAM (1332 MHz DDR3). All machines run x86-64 Debian Linux. Torque PBS was used to run multi-locality tests.

Figure 5 shows the execution times collected for the data access phase with a special test application executed on up to 16 localities and 1, 2, and 4 OS-threads per locality. The total number of distributed partitions was fixed at 32 to preserve the AGAS traffic pattern when run on a different number of localities; all partitions were uniformly distributed across the test localities. The number of separate, non-bulk queries to the distributed Shen EOS partitions was set to a fixed number of 16K. Each of these queries created a Future encapsulating the whole operation of sending the request to the remote partition, schedule and execute a HPX-thread, perform the interpolation based on the supplied arguments for the Shen EOS data, sending back the resulting values to the requesting HPX-thread, and resuming the HPX-thread which was suspended by the Future in order to wait for the results to come back.

The graph demonstrates that the overhead of distributed table implementation does not increase significantly over the entire range of available localities. While the scaling is much better when the number of localities remains small (up to 4), the overall time required to service the full 16K data lookup requests remains roughly constant. The test application itself does not execute any work besides querying and interpolating the distributed tables, which does not leave much room to overlap the significant network traffic generated with useful computation. This causes the scaling to flatten out beyond 8 localities. Using the distributed tables in real applications doing much more work will allow to further amortize the introduced network overheads. The results also imply that a single AGAS server is quite capable of servicing at least 16
client localities, especially considering the intensity of request traffic over Ethernet interconnect deployed in our testbed. We plan to further evaluate this aspect of distributed table implementation using faster interconnect networks, such as Infiniband.

V. RESULTS

Accessing a single, potentially distributed Shen equation of state table using multiple threads for converting conservative variables to primitives and vice versa as required for the flux-conservative HRSC method results in a slowdown when compared with using multiple independent copies of the table. There is also some additional overhead in using futures in the tabular access. In Figure 5, the table access slowdown relative to single core on a shared memory machine is presented. The results are a weak scaling test where the results for each workload have been normalized to the corresponding single core performance. In this test, each core accesses and interpolates 64k unique values in the table as a single bulk operation. Using HPX on a single core of an Intel Xeon X5660 processor, this test takes 0.0728 seconds; for comparison, using the Fortran codes provided at [14] access and interpolation of the exact same 64k values takes 0.0549 seconds, reflecting the increased overhead in using HPX. As the number of cores accessing the same table increases, the access performance degrades. The primary reason for that is the competition of hardware threads executing on the same processor for access to memory, since most of the interpolation requests cannot be satisfied solely from processor caches (for the machine used in test, the ratio of utilized fraction of EOS dataset to the aggregate size of L3 caches was about 5). This is compounded even further by the fact that accesses are sparse and random in nature, and therefore result in decrease of the effective memory bandwidth.

When no additional work is overlapped with the table access, the table access slowdown relative to a single core can reach as high as a factor of 3; however, when other workload is overlapped with the table access, the contention in table access is increasingly amortized. These results used the smaller (288 MB) table.

Fig. 6. The relative slowdown in table access when run across various numbers of cores on a shared memory machine. For comparison, results using OpenMP are also provided; all other results use HPX for table access. When no additional work is overlapped with the table access, the slowdown relative to that seen on a single core can reach as high as a factor of 3; however, when other workload is overlapped with the table access, the contention in table access is increasingly amortized. These results used the smaller (288 MB) table.

In Figure 7, the table access slowdown relative to the larger table is presented. This figure presents a weak scaling table access test where each core accesses and interpolates 64K different table queries. Because of the size of the table and the need for memory dedicated to the fluid field meshes and evolution, this table has to be distributed. The distributed results presented have been normalized to the corresponding two node performance. We use 8 cores in each node, consisting of two quad-core Intel Nehalem (2.8 GHz) processors with gigabit ethernet interconnect. The only workload provided was that of table access and interpolation; no additional workload was added. For this larger table, the relative slowdown in
In Figure 8 we evolve a neutron star with the Shen equation of state on a shared memory machine comparing Futures based table access with the traditional approach - reading in the table for each core. The table used in the comparison is the smaller (288 MB) Shen table. The simulation was unigrid with $50^3$ points across the computational domain. We find the relative slowdown in using Futures based table access compared to reading in the table on multiple cores to be extremely minimal – at worst a factor of 1.13 when table access is shared across 12 cores – with a considerable savings in memory. These results resemble the $14 \mu s$ workload line seen in Figure 6.

less than $\sim 15\%$, and often much less than that. This added cost is justifiable, since as larger tables become available in simulation efforts, astrophysics simulations can then achieve a more realistic description of hot nuclear matter and incorporate more microphysics, including neutrino transport. Managing large tables in this asynchronous way would be difficult to implement when using conventional programming models, such as MPI.

Several key improvements to the results presented here are currently underway. As the HPX runtime system becomes NUMA aware, much of the memory contention observed here in both OpenMP and HPX runs can be eliminated [21]. Ways to reduce the Futures overhead reported in Fig. 8 even further are currently under investigation. All distributed runs presented here used gigabit Ethernet interconnect; however, HPX support for the native Verbs interface for Infiniband is also underway. Hardware support for AGAS translation, whose first-cut implementation could utilize FPGA (Field-Programmable Gate Array) technology, promises to reduce key overheads, both in execution and storage, related to the software implementation. OpenCL support via percolation in HPX is also under development and could substantially impact the capability to perform neutrino transport in neutron star simulations.

As a final note, we point out that switching from a message passing to message driven style computation for neutron star simulations has significant performance impacts beyond just those discussed in this paper involving the finite temperature
equation of state tables. While those improvements are outside the scope of this work, the key concepts of managing asynchrony, amortizing contention, and hiding network latency make a significant positive impact in the scalability of neutron star simulations.

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