NUMA-aware Scheduling and Memory Allocation for data-flow task-parallel Applications

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Abstract
Dynamic task parallelism is a popular programming model on shared-memory systems. Compared to data parallel loop-based concurrency, it promises enhanced scalability, load balancing and locality. These promises, however, are undermined by non-uniform memory access (NUMA) systems. We show that it is possible to preserve the uniform hardware abstraction of contemporary task-parallel programming models, for both computing and memory resources, while achieving near-optimal data locality. Our run-time algorithms for NUMA-aware task and data placement are fully automatic, application-independent, performance-portable across NUMA machines, and adapt to dynamic changes. Placement decisions use information about inter-task data dependences and reuse. This information is readily available in the run-time systems of modern task-parallel programming frameworks, and from the operating system regarding the placement of previously allocated memory. Our algorithms take advantage of data-flow style task parallelism, where the privatization of task data enhances scalability through the elimination of false dependences and enables fine-grained dynamic control over the placement of application data. We demonstrate that the benefits of dynamically managing data placement outweigh the privatization cost, even when comparing with target-specific optimizations through static, NUMA-aware data interleaving. Our implementation and the experimental evaluation on a set of high-performance benchmarks executing on a 192-core system with 24 NUMA nodes show that the fraction of local memory accesses can be increased to more than 99%, resulting in a speedup of up to 5× compared to a NUMA-aware hierarchical work-stealing baseline.

1. Introduction
High-performance systems are composed of hundreds of general-purpose computing units and dozens of memory controllers to satisfy the ever-increasing need for computing power and memory bandwidth. Shared memory programming models with fine-grained concurrency have successfully harnessed the computational resources of such architectures (Blumofe et al. 1995; Pratikakis et al. 2011; OpenMP Architecture Review Board 2013; Planas et al. 2011). Dynamic task parallelism is a popular programming model on shared-memory systems. Compared to data parallel loop-based concurrency, it promises enhanced scalability, load balancing and locality. These promises, however, are undermined by non-uniform memory access (NUMA) systems. We show that it is possible to preserve the uniform hardware abstraction of contemporary task-parallel programming models, for both computing and memory resources, while achieving near-optimal data locality. Our run-time algorithms for NUMA-aware task and data placement are fully automatic, application-independent, performance-portable across NUMA machines, and adapt to dynamic changes. Placement decisions use information about inter-task data dependences and reuse. This information is readily available in the run-time systems of modern task-parallel programming frameworks, and from the operating system regarding the placement of previously allocated memory. Our algorithms take advantage of data-flow style task parallelism, where the privatization of task data enhances scalability through the elimination of false dependences and enables fine-grained dynamic control over the placement of application data. We demonstrate that the benefits of dynamically managing data placement outweigh the privatization cost, even when comparing with target-specific optimizations through static, NUMA-aware data interleaving. Our implementation and the experimental evaluation on a set of high-performance benchmarks executing on a 192-core system with 24 NUMA nodes show that the fraction of local memory accesses can be increased to more than 99%, resulting in a speedup of up to 5× compared to a NUMA-aware hierarchical work-stealing baseline.

2. NUMA-aware optimizations
To achieve the goals above, it is necessary for the run-time system to gain full control over task and data placement, as any static
placement may conflict with the dynamic control flow of complex applications or dynamic load-balancing in the run-time itself. Such a run-time system needs a dynamic placement algorithm that ensures task input and output data are local and that interacts gracefully with work-stealing:

- The first step is to avoid making early placement decisions which could later prove sub-optimal. In particular, the memory to store task output data should not be allocated until the task placement is known. Our new technique, called deferred allocation, hands over the responsibility of allocating memory to the producer task, on its local NUMA node. This is made possible through the privatization of task output data.

- The second step is to enhance the locality of read memory accesses. Since the inputs of a task are outputs for another task, the location of input data is determined when the producer task executes. This advocates for an enhanced work-pushing technique, building on the algorithm proposed by Drebes et al. (Drebes et al. 2014), and revising it to together with deferred allocation: a task is placed according to the location of its input data before allocating memory for its outputs.

This combination of enhanced work-pushing and deferred allocation is fully automatic, application-independent, portable across NUMA machines and transparently adapts to dynamic changes at run time. These techniques require detailed information about the affinities between tasks and data, but this information is either readily available or can be obtained automatically in the run-times of recent task-parallel programming models, such as StarSs (Planas et al. 2009), OpenMP 4 (OpenMP Architecture Review Board 2013), SWAN (Pratikakis et al. 2011) and OpenStream (Pop and Cohen 2013), which allow the programmer to make inter-task data dependencies explicit. While specifying the precise task-level data-flow rather than synchronization constraints alone requires more initial work for programmers, this effort is more than offset by the resulting enhanced performance and performance portability.

3. Experimental evaluation

Our test system is an SGI UV2000 with 192 cores and 756GiB RAM, distributed over 24 NUMA nodes, and running SUSE Linux Enterprise Server 11 SP3 with kernel 3.0.101-0.46-default. The system is organized in blades, each of which contains two Intel Xeon E5-4640 CPUs running at 2.4GHz. Each CPU has 8 cores and has direct access to a memory controller. From a core’s perspective, a memory controller can be either local if associated to the same CPU, at 1 hop if on the same blade, at 2 hops if on a different blade that is connected directly to the core’s blade or at 3 hops if on a remote blade with an indirect connection.

Figures 1 and 2 show respectively the improvement in locality of memory accesses and speedup of five variants of each benchmark against a parallel baseline. The baseline is a state-of-the-art data-flow implementation that relies on NUMA-aware hierarchical work-stealing to enhance locality. The optimized variants use our work-pushing optimization with either input only, output only or a weighted heuristic or deferred allocation (dfa) alone or along with the input only heuristic.

Figure 1 shows that our optimizations allow reaching a near-optimal locality of memory accesses, up to 99.8%. Figure 2 shows the speedup of the optimizations over the parallel baseline, reaching up to 5× speedup. The best performance is systematically achieved by combining work-pushing with deferred allocation. The significant performance improvement results from better locality.

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References


