

A High-Performance Design for Hierarchical Parallelism in the QMCPACK Monte Carlo code

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Abstract—We introduce a new high-performance design for parallelism within the Quantum Monte Carlo code QMCPACK. We demonstrate that the new design is better able to exploit the hierarchical parallelism of heterogeneous architectures compared to the previous GPU implementation. The new version is able to achieve higher GPU occupancy via the new concept of crowds of Monte Carlo walkers, and by enabling more host CPU threads to effectively offload to the GPU. The higher performance is expected to be achieved independent of the underlying hardware, significantly improving developer productivity and reducing code maintenance costs. Scientific productivity is also improved with full support for fallback to CPU execution when GPU implementations are not available or CPU execution is more optimal.

Index Terms—Heterogeneous computing, GPUs, Monte Carlo

I. INTRODUCTION

QMCPACK, is a modern high-performance open-source Quantum Monte Carlo (QMC) [1] simulation code [2], [3]. Its main applications are electronic structure calculations of molecular, nanoscale and solid-state systems. Variational Monte Carlo (VMC), diffusion Monte Carlo (DMC) and several other advanced QMC methods are implemented with highly optimized algorithms. These algorithms sample the positions of electrons within the simulated system to accurately compute quantum mechanical properties. Their actual implementations in QMCPACK are called QMC drivers. When QMCPACK development started in the beginning of the first decade of this century, there were initially only multi-threaded CPU drivers. With over 15 years of development, QMCPACK has been well optimized to run on multicore

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CPU-only supercomputers like Cori at the National Energy Research Scientific Computing Center (NERSC) and Theta at the Argonne Leadership Computing Facility (ALCF). When NVIDIA GPUs emerged in the field of high-performance computing, GPU dedicated QMC drivers were introduced by using Compute Unified Device Architecture (CUDA). They perform extremely well on supercomputers with a CPU-GPU hybrid architecture like Summit at the Oak Ridge Leadership Computing Facility (OLCF), though at the cost of portability. The CUDA-based GPU drivers are completely incompatible with CPU-only drivers and call separate sets of subroutines of the wavefunction calculation. This is required due to the different data layouts and algorithms needed for high-performance on the GPUs [4]. For this reason, close to redundant feature implementations are needed to satisfy both architectures. If a feature implementation is missing in the GPU drivers, the whole simulation needs to run with a CPU-only build because mixing CPU and GPU features is not supported and the CPU/GPU selection is made at compile time.

As supercomputers start to reach Exascale and architectural diversity has increased, and CUDA is no longer the only GPU programming model available. We must find approaches to efficiently address the different hardware [5]. The current Top500 rank-1 supercomputer, the AMD-based Frontier at OLCF, generally prefers Heterogeneous-Computing Interface for Portability (HIP) due to the installed AMD GPUs. To a large degree, CUDA source code can be treated as HIP code directly, and be easily compiled for AMD GPUs, making the portability issue not significant. However, on the Intel-based Aurora machine at ALCF, SYCL is the preferred programming model for Intel designed GPUs. The trick that treats CUDA as HIP won't work for SYCL considering the fundamental difference between CUDA and SYCL. The QMCPACK developers have already been struggling with maintaining both a CPU based and a CUDA based GPU implementation. Adding additional drivers for each preferred programming model is clearly not a sustainable direction.

In this work, we introduce a new universal design of batched QMC drivers which may replace all the previous QMC drivers. The added flexibility in these drivers enables maximizing code performance on specific hardware once users match parallelism hierarchies properly to the actual software and hardware. The new design supports the necessary data movement to allow mixing CPU-only and GPU accelerated features to ensure a feature complete QMCPACK experience for the user regardless of the hardware being used. Code specialization for specific hardware remains possible for achieving potentially higher performance although this no longer needs to be at the driver level.

This paper is organized as follows. Sec. II analyzes the DMC algorithm and its implementation before the new batched drivers are added. Sec. III introduces the details of the new drivers. Sec. IV shows how the code behaves in CUDA-based GPU drivers and the new drivers, and discusses application performance. Sec. V summarizes the hierarchical parallelism in QMCPACK.

II. QMC DRIVERS WITHOUT THE BATCHED DESIGN

A. Basic QMC algorithm

Before analyzing all the three sets of drivers, let us first understand the characteristics of a DMC algorithm shown in Alg. 1.

Algorithm 1 Pseudocode for diffusion Monte Carlo.

```

1: for MC generation = 1 ··· M do
2:   for walker = 1 ···  $N_w$  do
3:     let  $\mathbf{R} = \{\mathbf{r}_1 \dots \mathbf{r}_N\}$ 
4:     for particle  $k = 1 \dots N$  do
5:       set  $\mathbf{r}'_k \leftarrow \mathbf{r}_k + \nabla_k \Psi_T(\mathbf{R}) + \delta$ 
6:       let  $\mathbf{R}' = \{\mathbf{r}_1 \dots \mathbf{r}'_k \dots \mathbf{r}_N\}$ 
7:       ratio  $\rho = \Psi_T(\mathbf{R}') / \Psi_T(\mathbf{R})$ 
8:       derivatives  $\nabla_k \Psi_T(\mathbf{R}')$ 
9:       Accept  $\mathbf{r}_k \leftarrow \mathbf{r}'_k$  or reject
10:      end for{particle}
11:      local energy  $E_L = \hat{H} \Psi_T(\mathbf{R}) / \Psi_T(\mathbf{R})$ 
12:    end for{walker}
13:    reweight and branch walkers based on  $E_L - E_T$ 
14:    update  $E_T$  and load balance via MPI.
15:  end for{MC generation}

```

- L1. The loop over generations is a sequential time-stepping loop for the DMC imaginary time evolution.
- L2. The walker evolution at each generation is independent of each other and thus this loop can be parallelized. On parallel computers, walkers are first parallelized over Message Passing Interface (MPI) and then parallelized within each MPI process. Due to the fact that MPI is only needed for aggregating results and handle walker count imbalance in L14, the parallel efficiency of QMC algorithms over MPI can be made nearly perfect [2], even at a scale of thousands to millions of MPI processes. For the rest of this work, we restrict the discussion of parallelization schemes of walkers within an MPI process.

- L4. The loop of over particles (electrons) during random walking is also sequential. Each iteration is called a single particle move since only one particle of a walker is moved. This algorithm is referred to as particle-by-particle moves.
- L5-6. Proposing a new electron position requires relatively cheap computation.
- L7-8. When a single particle move gets proposed, heavy computational routines contain another vector loop over all the orbitals or particles.
- L9. The computational cost depends on whether a proposed move gets accepted or rejected. Upon accepting a move, additional computation is needed to update the internal data of a walker, including a determinant matrix inverse which contributes the leading term of algorithmic complexity. Rejecting a move doesn't need computation and results near zero cost. This line causes the major computational cost difference at each single particle move. In VMC simulations, the acceptance ratio is typically between 20–80%. However, within the more costly DMC, the acceptance ratio is usually very high (> 99%).
- L11. Energy evaluations are required for every walker after single particle moves. They are expensive.

B. Multi-threaded CPU drivers

Algorithm 2 Pseudocode for the multi-threaded CPU implementation.

```

1: for MC generation = 1 ··· M do
2:   #pragma omp parallel for
3:   for walker = 1 ···  $N_w$  do
4:     for particle  $k = 1 \dots N$  do
5:       ...
6:     end for{particle}
7:   end for{walker}
8: end for{MC generation}

```

On multi-core CPUs, the multi-threaded CPU driver implementation distributes walkers over CPU cores via OpenMP threads as shown in Alg. 2. The needed code change is minimal. Although the cost of each single particle move depends on whether the proposed move is accepted or rejected, the overall cost of each walker is almost equal once the single particle move loop completes given the acceptance ratios across walkers. Thus, the load-balance of threads is also near perfect. In the CPU implementation, we also adopt OpenMP `simd` directives for the vector loop mentioned in Algo. 1 to leverage the Single instruction, multiple data (SIMD) units on modern CPUs [6]. This parallelization strategy works extremely well on many-core wide vector CPUs including Intel Xeon, AMD EPYC and Fujitsu A64FX processors.

C. CUDA-based GPU drivers

The introduction of GPUs in HPC challenged the above parallelization strategy. The accelerator characteristics of GPUs

require sufficiently heavy compute kernels to amortize kernel submission or synchronization cost in microseconds. In the multi-threaded CPU drivers, each compute routine only handles the work of a single walker. For large simulation problems (> 1000 electrons), the workload of a single walker can keep GPUs busy. But many QMCPACK users run small to medium problem sizes ($<= 1000$ electrons) in scientific production, so dispatching GPU computation from multi-threaded CPU drivers results in slow execution with most of the time being spent in GPU overhead. For this reason, a GPU friendly scheme [4] was devised and implemented in the CUDA-based drivers in QMCPACK.

Algorithm 3 Pseudocode for the CUDA-based implementation.

```

1: for MC generation = 1 ··· M do
2:   for particle  $k = 1 \dots N$  do
3:     Algorithm 1. Line 5,6,7,8,9 over all the  $N_w$  walkers
4:   end for{particle}
5:   local energy  $E_L = \hat{H}\Psi_T(\mathbf{R})/\Psi_T(\mathbf{R})$  over  $N_w$ 
6:   reweight and branch walkers based on  $E_L - E_T$ 
7:   update  $E_T$  and load balance via MPI.
8: end for{MC generation}

```

In Alg. 3 it appears that the loop over walkers in Alg. 1 disappeared. Actually it is not removed but is added inside each of the computational routines previously serving only one walker at a time. All the computational routines on L3 now handle all the walkers in a batched operation. As a result, all the walkers advance in lock-step for each single particle move. All the compute kernels expose both vector computation and walker concurrency and fit extremely well the hierarchical design of GPUs with threads and thread blocks. For small simulated systems, GPUs have sufficient memory to enable batching over hundreds to thousands of walkers. This is sufficient to hide most of the GPU kernel overhead in practice.

However, this scheme has a few limitations: (a) In the operation of accept/reject a single particle move, the number of walkers with their proposed moves accepted must be large enough to avoid leaving part of the compute hardware idle. (b) There is only one thread enqueueing kernels and handling synchronization, while all the other threads are idle. When the only working host thread is occupied with handling of pre-/post-kernel processing, the GPU is also left idle. (c) Most of the time, there is only one CUDA stream being used and there is limited overlap between kernel execution and data transfer or concurrent kernel execution. Using multiple CUDA streams can be added but requires significant code implementation. (d) Assigning one thread block per walker only works for small problem sizes. It doesn't allow leveraging more thread blocks per walker to further speed up the computation. Meanwhile, large problems cannot keep many walkers resident on GPU due to the device memory capacity limit and thus limits the full use of hardware resources.

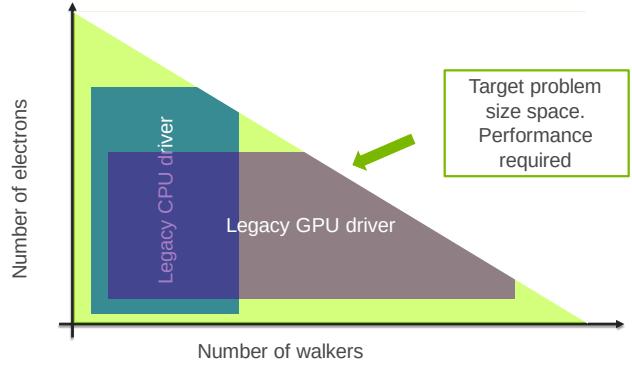


Fig. 1. Parameter space of efficient runs with multi-threaded CPU (teal) or GPU (grey) driver.

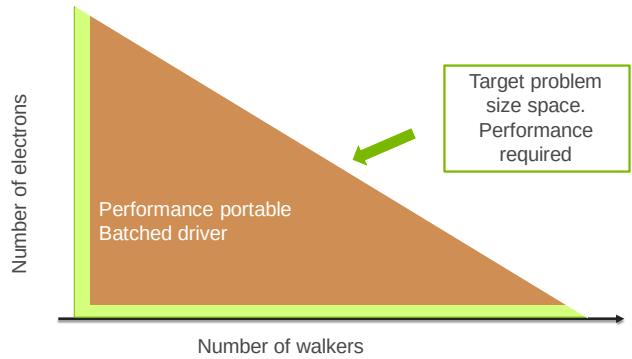


Fig. 2. Parameter space of efficient runs with batched drivers (brown).

D. Deficiency of multi-threaded and CUDA-based drivers

Constrained by their pre-determined parallelization schemes, either of the above driver designs only works efficiently in a limited parameter space as illustrated in Fig. 1. The lower triangle parameter space restriction comes from memory capacity limits. In addition, the multi-threaded CPU drivers only invoke single walker APIs while CUDA-based drivers only invoke “batched” or multi walker APIs. Due to the difference in data layout and assumptions of data locations, it is not possible to fallback from one implementation to the other and every feature must be implemented separately for both multi-threaded CPU and GPU drivers. i.e. The CPU and GPU codes were effectively internal forks of the codebase. This is clearly undesired due to the additional developer effort and added maintenance cost. Only compute-heavy features are worth porting to GPUs and running light computation on CPUs is usually sufficient.

With the above deficiency in mind, here we introduce a new high-performance design for the QMC drivers and overall application. It avoids diverging code paths at the driver level and works efficiently in the full possible parameter space as illustrated in Fig. 2.

III. PERFORMANCE PORTABLE BATCHED DRIVERS

QMC drivers implemented in the new design are called batched drivers as walkers are handled by compute devices in batches. This applies even for CPU based machines, although a batch size of one is selectable, recovering close-to the old CPU-only algorithm. Before explaining the design detail, we first introduce a new concept “crowd”, as a sub-organization of the walker population. A crowd is a subset of the walkers that are operated on as a single batch. Walkers within a crowd move through the operations of the QMC algorithm in lock-step. Walkers in different crowds remain fully asynchronous unless operations over the full population are needed.

The batched DMC driver pseudocode is shown in Alg. 4. Compared to the multi-threaded CPU implementation, the threaded loop over walkers has been replaced with a threaded loop over crowds and thus crowds are fully parallelized over host threads. The performance of multi-core CPUs can be easily maximized as long as the number of crowds is chosen equal to the core count. When the crowd size equal to 1, batched drivers behave exactly as multi-threaded CPU drivers. With the crowd size larger than 1, the throughput of generating statistical samples can potentially further increase due to improved data reuse or data locality.

Compared to the CUDA-based implementation, the unchanged walker operation in batches ensures dispatching sufficiently heavy computation in each GPU invocation. The added multi-threaded crowds enable further improvements to GPU utilization. When the number of crowd is restricted to one, batched drivers behave exactly as CUDA-based drivers. With more than one crowd, crowds parallelized over host threads concurrently sending operations to GPUs; data transfer and kernel execution from different crowds may overlap if the underlying hardware allows. Thus, the first three limitations of the CUDA-based implementation are removed. Considering that the batched drivers do not mandate specific data layouts, the last limitation of the CUDA-based implementation can be removed by specializing compute kernels for extremely large problem sizes.

With the added crowds, batched drivers have a flexible number of batches and batch sizes which can be tuned to maximize the performance of underlying hardware. In the new driver design, the old set of walker batched computational routines used by CUDA-based drivers are replaced with a new set which allow falling back to computation using the single walker APIs. Consequently, batched drivers allow mixing and matching CPU-only and GPU-accelerated features in a way that is neither feasible with the multi-threaded CPU implementation nor the CUDA-based GPU one.

IV. RESULTS

A. Demonstrating concurrent execution via GPU tracing

In order to verify that batched drivers behave as expected on GPUs with real simulations, we use NVIDIA Nsight Systems to trace GPU activities on an NVIDIA GPU when running a QCMPACK performance test, which is a NiO 8-atom supercell

Algorithm 4 Pseudocode for the batched DMC driver.

```

1: for MC generation = 1 ··· M do
2:   #pragma omp parallel for
3:   for crowd = 1 ··· C do
4:     for particle k = 1 ··· N do
5:       Algorithm 1. Line 5,6,7,8,9 over all walkers with
       in this crowd
6:     end for{particle}
7:     local energy  $E_L = \hat{H}\Psi_T(\mathbf{R})/\Psi_T(\mathbf{R})$  over this
       crowd
8:     reweight and branch walkers based on  $E_L - E_T$ 
9:     update  $E_T$  and load balance via MPI.
10:   end for{crowd} CG
11: end for{MC generation}

```

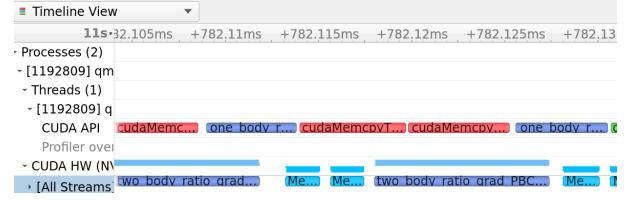


Fig. 3. CUDA-based GPU driver GPU activity tracing. GPU API calls are made from a single thread and kernel execution and data transfers are all serialized.

DMC simulation with 512 walkers. This is a “small” system where kernels are small and therefore hiding kernel latency and maximizing concurrency is critical to performance. Fig. 3 shows the tracing of this test using the CUDA-based DMC driver. There is only 1 thread active even though there are 4 OpenMP threads available to the process. Kernel execution and data transfer are serialized. Fig. 4 shows the tracing of the same test using the new batched DMC driver. All the 4 OpenMP threads enqueue kernels and submit data transfers to the GPU dedicated to this process. The GPU keeps servicing requests from threads to maximize its utilization. Both concurrent kernel execution and overlapping kernel execution and data transfers are observed in the tracing. Higher efficiency is clearly obtained.

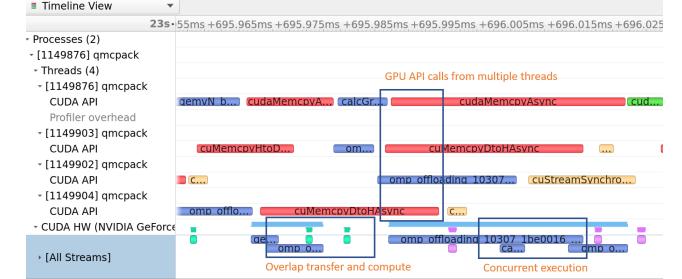


Fig. 4. Batched driver GPU activity tracing. GPU API calls are made from multiple threads. Both concurrent kernel execution and overlapping kernel execution and data transfers are observed.

B. Demonstrating gain in throughput on NVIDIA GPUs

When targeting GPUs, the batched drivers currently use OpenMP offload and vendor linear algebra libraries. Their performance are compared to the CUDA-based drivers. The comparison is not apples to apples. In general, the batched drivers have fewer pieces of features running on GPUs and additional data transfer can be necessary between the GPU and the host. Although all the features used in the NiO performance tests are accelerated in both the CUDA-based and batched drivers, the implementations still differ due to the fundamental design change in the batched drivers. And for the old CUDA-based drivers, all the kernels were handwritten and highly optimized in CUDA while the performance of batched drivers are affected by the quality of kernels generated by the OpenMP offload compilers. Here we can compare the performance of both drivers by the sampling throughput, namely the number of samples generated in a given time. The study was conducted on the Summit supercomputer at Oak Ridge National Laboratory. Each Summit node contains dual socket IBM Power 9 processors with 42 CPU cores in total and 6 NVIDIA V100 GPUs. The optimal way of running QMCPACK requires 1 MPI rank per GPU. Thus, on each node, we place 6 MPI ranks and each MPI process has its dedicated 7 CPU cores and 1 GPU.

Both the CUDA-based GPU drivers and batched drivers require optimizing the walker count to maximize the throughput of a single GPU. Typically, the greatest number of walkers prior to exhausting GPU memory is optimal. In Fig. 5, the throughput of the runs with the CUDA-based driver increases rapidly as walker count increases. It quickly saturates at 1792 walkers once a single thread performance gets maxed out. With the batched DMC driver, throughput grows slower in small walker counts. When the total walker count per MPI rank is fixed, the walker batch size per thread is smaller in batched drivers and thus in total more GPU overhead gets exercised by all the threads. At larger walker counts when single thread maximal performance is reached, batched drivers have more potential to maximize the full GPU throughput by leveraging available threads. For this benchmark problem, the measured performance becomes higher than the CUDA-based GPU driver when the walker count exceeds 2000.

We also benchmark the code performance for a wide range of problem sizes. The benchmark uses DMC simulations of NiO solids with 16, 32, 64, 128 and 256 atoms in the simulation cell. In Fig. 6 the throughput of each problem size is rescaled by the throughput of CUDA-based GPU driver runs. When running CPU-only, the relative throughput is only 10% which reflects the fact that most of compute power on Summit is from the NVIDIA V100 GPUs and the CUDA-based DMC driver is very well optimized. Our newly designed batched DMC driver shows 80% to 115% relative performance depending on the problem size. It is already suitable for scientific production simulations due to its competitive high-performance and feature complete nature. With further optimization, we expect that the batched drivers will exceed

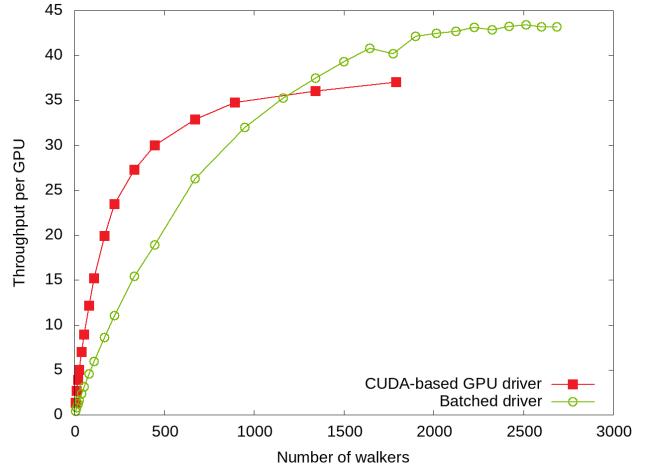


Fig. 5. Sampling throughput as a function of walker counts in the 32 atom cell NiO solid DMC simulation.

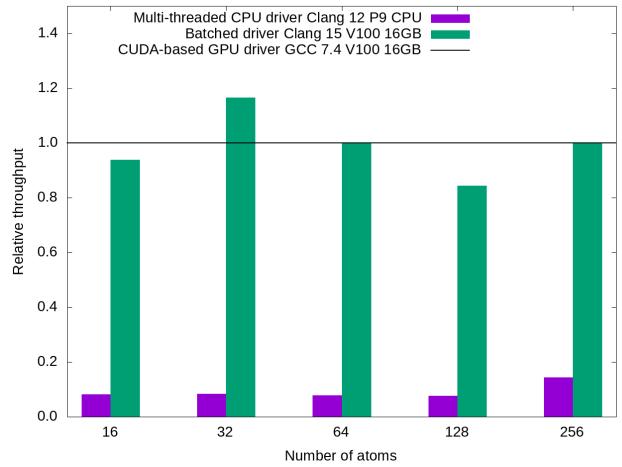


Fig. 6. Batched driver throughput compared with the CUDA-based GPU driver.

the CUDA-based driver in all the benchmark cases. As of August 2022, the compilers and libraries on non-NVIDIA platforms were not yet mature enough for benchmarking. We plan to evaluate them once compilers and runtime libraries are sufficiently mature.

V. CONCLUSION

Here we summarize the high-performance design of hierarchical parallelism in QMCPACK from the coarse level to the fine level as implemented in the batched drivers.

- 1) Fully MPI distributed walker population. Usually one MPI per CPU socket or GPU. Extremely good strong and weak scaling across thousands to millions of compute nodes.
- 2) Multi-threaded crowds handle walkers within each MPI process. Each crowd does its independent time evolution. This is highly scalable on multi-core CPUs. In a CPU-GPU hybrid architecture, crowds may maximize the

utilization of CPU cores before the shared GPUs are saturated by the workload.

- 3) Batched computation of walkers within each crowd. On GPUs, their computations can be submitted to GPUs with minimal GPU API overhead. On CPUs, there remains the possibility of breaking them into smaller tasks which can run on additional CPU threads if they are available.
- 4) Compute kernels of each walker operate on a set of orbitals, usually the same or more than the electron count, or all the electrons. They can be fully vectorized on single instruction, multiple threads (SIMT) and single instruction, multiple data (SIMD) hardware. For extremely large problem sizes, these vector loop can be broken up in order to leverage more threads on CPUs or thread blocks on GPUs.

By matching these parallelism levels to appropriate software abstractions in a high-performance parallel computer, we believe that the maximal code performance can be achieved regardless of the underlying hardware and true performance portability can be achieved across CPU/GPU and even accelerators from any vendor, potentially also including FPGAs and ASICs. In future work we plan to demonstrate this portability.

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