The NAS Parallel Benchmarks 2.1 Results

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Abstract

We present performance results for version 2.1 of the NAS Parallel Benchmarks (NPB) on the following architectures:

- IBM SP2/66 MHz
- SGI Power Challenge Array/90 MHz
- Cray Research T3D
- Intel Paragon

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1 Introduction

The NAS Parallel Benchmarks (NPBs) [1, 2] are a widely-recognized suite of benchmarks originally designed to compare the performance of highly parallel computers with that of traditional supercomputers. The NPBs are specified algorithmically, and are implemented mainly by computer vendors, using techniques and optimizations appropriate to their specific computers. Performance results based on these optimized proprietary implementations are submitted to NAS by vendors and are reported in a periodic NAS Technical Report [4]. The vendor-optimized NPB implementations will be referred to as NPB 1.

In late 1995, NAS announced NPB 2[3], a set of specific NPB implementations, based on Fortran 77 and MPI[5]. NPB 2 implementations are intended to be run with little or no tuning, in contrast to NPB 1 implementations, which have been highly optimized by vendors for specific architectures. NPB 2 implementations are designed for computers with hierarchical cache-based memories.

Unlike that of proprietary NPB 1 implementations, the source of NPB 2 implementations is freely available. One advantage of this is that anyone can run them on any machine, allowing collection of data on a much wider variety of machines and configurations. Another is that the techniques used in NPB 2 implementations can be studied for possible use in other codes.

Because they have not been optimized by vendors, NPB 2 implementations approximate the performance a typical user can expect for a portable parallel program on a distributed memory parallel computer. Together the results presented here provide a well-calibrated comparison of the real-world performance of several parallel computers. Furthermore, by comparing NPB 2 results to NPB 1 results, we can draw conclusions about how easy it is to obtain high performance on these systems. NPB 2 results complement, rather than replace, NPB 1 results.

NPB 2.1, upon which the results in this paper are based, was released in February, 1996. It contains implementations of 5 of 8 of the original NAS benchmarks - the three pseudo-applications LU, SP and BT, and the kernels MG and FT. NPB 2.2 will include the remaining benchmarks - CG, IS and EP - as well as a revised FT, which was found to have some scalability and performance problems. This paper therefore includes results for LU, SP, BT and MG only. A future paper will contain results for all 8 benchmarks.

This paper also includes the first results for the NPB class "C" sizes that were first described in the NPB 2.0 report.

2 Methodology

NPB 2 presents a number of challenges and opportunities that were not present in NPB 1. NPB 1 implementations represent a best case scenario: they are implemented and carefully optimized by vendors (and the codes remain proprietary); they are run by vendors in ideal conditions in clean environments with the latest software. NPB 1 results are meaningful and can be compared because every vendor has had equal opportunity to optimize, and because the pencil-and-paper nature of the benchmarks eliminates architectural bias. NPB 1 results, while far more meaningful than the "not to be exceeded" peak performance and LINPACK[6] rates, generally represent upper limits on what can be achieved for the type of calculations performed by the NPBs.

In contrast, NPB 2 implementations are run essentially "out of the box" with no tuning[1]. Because the NPB 2 codes are not proprietary, and source is readily available and easy to build, anyone can generate NPB 2 results. The environment in which the benchmarks are run may not include the latest software and hardware, may not include all the special tuning tricks known to vendors, and may not be as clean as that used by vendors. As with any scientific measurement, benchmark results are useless unless reproducible. Therefore great care must be taken to document the specific conditions under which measurements were made - compiler options, MPI and compiler versions, system software version, etc.

In this report, section 6 describes the environment in which the measurements were taken. The conditions were the best available to NAS when the measurements were made. While the environment description may make the results more difficult to understand (especially when there are several sets of results for the same "machine" with slightly different configurations),

[1] NPB 2 permits two levels of tuning: 0% code modification and 5% code modification. This report contains results only for the 0% case

data qualified in this way can provide a well-calibrated measurement of the effect of small hardware and software changes - showing the improvement or regression of system performance over time.

All NPB 2 implementations discussed in this paper run a single solver iteration and reset the initial conditions before starting the the timed portion of the benchmark. This procedure eliminates startup time overhead that can severely skew results for short-running benchmarks. It also means that Mflop/s rates reported by the code will not be the same as Mflop/s rates reported by a hardware instruction counter. Care must be taken to reconcile directly-measured operation counts with the rates reported by the codes themselves. The measurements can be reconciled by directly measuring the operation count of zero-iteration run and subtracting this from the operation count of a complete run. The time reported by the benchmarks and in this report is wallclock time. CPU time has little meaning in a tightly-coupled parallel program where time spent blocking for messages may not be counted as CPU time.

3 Applicability and usefulness of the results

3.1 Vector vs. Cache architectures

In this paper we report results only for machines based on RISC processors with cache-based memory hierarchies. While Fortran and MPI provide compile-and-run portability, it is much more difficult to obtain architectural portability, that is, to design a code that can run efficiently on both vector and RISC/cache architectures. In many cases, the requirements for a vector code (long vector length) directly conflict with those for a cache code (cache reuse). In some cases, it is possible to write a code that runs well on both, particularly when vendor-optimized libraries can be used. The NPBs do not use such libraries.

NPB 2 implementations are written specifically for cache-based architectures, and assume a fully distributed memory model, with communication only through MPI. While the codes can be run on a vector machine, such as a Cray J90, the results cannot be meaningfully compared with other results, except to point out the fact that compile-and-run portability does not necessarily mean architectural portability.

In this report we compare results from four machines. Three of these – the IBM SP2, Cray T3D, and Intel Paragon with GP nodes – have completely distributed memory. One – the SGI Power Challenge Array – is composed of SMP nodes.

A few types of machines, including traditional networks of workstations, are not represented here but will be included in future reports.

3.2 Mflop/s rates

A new feature of NPB 2 is that we report results in Mflop/s (million floating point operations per second) as well as run time. The Mflop/s measure has little meaning for NPB 1, since different implementations may have substantially different operation counts. Since NPB 2 results are based on unmodified code (0% case), the operation count is approximately the same on any machine. Good optimizing compilers may be able to eliminate some operations, and others may add operations for certain reasons, so the reported Mflop/s rate may not be exactly what would be reported by a hardware instruction counter, but in our experience it is usually quite close (within a few percent).

The nominal rate is based on a combination of hand counting, hardware instruction counting (originally on Cray machines, more recently verified on an SP2) and extrapolation. The nominal floating point count does not change with number of processors - only with problem size - so any extra operations performed because of parallelization are not counted.

3.3 Comparison with NPB 1 results

In all cases, we compare NPB 2 results with NPB 1 results for the "same" machine. While this comparison is interesting, we do not want to overstate its significance. Roughly, the comparison shows the difference between what an "ordinary programmer" can achieve on a portable program and what an expert or unusually careful non-expert can achieve on an architecture-optimized program. If NPB 1 and NPB 2 timings are quite close, one might conclude that it is relatively easy to get "peak" (where peak means NPB-1 level) performance out of a particular machine. Different machines have substantially different results for this metric.

3.4 Comparing different configurations of the same type of computer

While the NPB suite was originally designed to compare different types of computers, it can also be used to probe certain minor differences within a single type of computer. For instance, the effect of using different compiler flags, different versions of the MPI library, and even different compilers (e.g., Fortran 90 vs. Fortran 77) can be measured. In this report, we use the NPB suite to explore different configurations of an SGI Power Challenge cluster, where a given number of processes may be distributed across nodes in many different ways.

3.5 Relevance for other codes

The NPB suite is based on computational fluid dynamics (CFD) codes typical of those run on the supercomputers at the NAS facility. We believe that the NPB 2 results are relevant to "the average user, with an average code," with a few caveats.

First, the NPB 2 implementations do not use numerical libraries. Codes that use vendor-optimized numerical libraries may obtain substantially better performance. Some library routines that could be useful for NPB implementations are FFT routines for the FT benchmark, a pentadiagonal solver for the SP benchmark and a block-tridiagonal solver for the BT benchmark. NPB 2 implementations do not use these because there do not exist standardized, vendor-optimized and widely available versions of the necessary routines (unlike the BLAS routines, which are less useful for the NPB problems).

Second, most NPB codes use fully implicit algorithms on a single grid that is distributed over several processors. Such algorithms require more communication than explicit methods or hybrid methods that solve implicitly on a single processor with explicit updates between processors. Compared to codes using these other algorithms, the NPB suite provides a more stringent test of interprocessor communication, and may show poorer scalability. Counteracting this is the fact that the NPB 2 codes use good parallel algorithms that minimize communication.

Third, NPB problems are idealized versions of real-world problems. They are more regular than typical real-world problems (making load balancing easier) and boundary conditions and physics have been somewhat simplified. The effects on performance are complicated. For instance, load-imbalance from boundary calculations is probably smaller than in engineering applications, but having fewer operations per grid point per time step (because of simpler physics) gives a higher communication to computation ratio.

For these reasons and others, performance of real-world codes may or may not be similar to NPB performance. The main use of NPB is, instead, to compare the performance of different computers on the general class of codes represented by the NPBs.

4 Machines

The results presented in this report were collected on an IBM SP2, an Intel Paragon, an SGI Power Challenge Array, and a Cray T3D.

4.1 NAS IBM SP2

IBM SP2 results were collected on the machine located at the Numerical Aerodynamic Simulation (NAS) facility at NASA Ames Research Center. This SP2 contains 160 "wide" nodes, each with a single POWER-2 processor running at at 66.5 MHz, and with a theoretical peak performance of 266 Mflop/s. The nodes are connected by a high performance switch. All nodes have at least 128 MB of main memory.

The key feature of wide nodes, for the purposes of this report, is that they have (when configured with the right number of memory cards) a very wide (256 bit) path between the processor and main memory that provides extraordinary memory bandwidth (about 2 GByte/s per processor). They also have a 256 KB primary cache with 256-byte cache lines. These figures are twice and four times what is available on the so-called "thin-node 2" and "thin-node", respectively.

IBM has implemented an optimized version of MPI for the SP2. The point-to-point bandwidth of this MPI is about 35 MB/s. The latency is about 55 μs.

The following software was used for the results presented in this paper:

- AIX version 4.1.3
- POE version 2.1 (includes MPI)
- XL Fortran version 3.2

The following compiler flags were used in compiling all NPB 2 codes (all but the last are defaults on the NAS system, but not on all SP2 systems):

- -qcache=type=d:level=1:size=256,-qarch=pwr2 -O3

The nodes of the NAS SP2 are always dedicated to a single user process. Many of the results were collected when other jobs were running on the system. The only effect these jobs would have would be on placement of processes and switch contention. Neither of these has had a noticeable effect on system performance for the number of nodes on which we collected results. All codes were run three times. The best times were chosen for this report. IBM provides a "high priority" mode to run applications. This is not turned on by default on the NAS machines, and we did not use it. It allows the effect of competing system processes to be minimized.

4.2 NAS SGI Power challenge array

The SGI Power Challenge Array located at NAS is a cluster containing 4 Power Challenge SMP nodes, each with 8 R8000 processors running at 90 MHz. (The NAS system includes a few other nodes, but they were not used for this report). Each processor has a peak floating point performance of 360 Mflop/s. For a few of the measurements, we moved 18 processors into a single node and ran code on that single node. See section 6 for more details.

Each of the 4 nodes has two HIPPI connections. All HIPPI connections are switched on a single switch.

SGI has implemented an optimized MPI for the Power Challenge Array. Within a single node, MPI transfers are done through a single-copy mechanism, achieving 64 MB/s bandwidth and 18 μs latency. Between nodes, transfers are done with a special HIPPI driver that bypasses (but coexists with) IP traffic. MPI transfers over HIPPI achieve about 110 μs latency and 92 MB/s bandwidth. Very large data transfers are striped across multiple HIPPI connections, giving about 160 MB/s over 2 HIPPI connections. None of the NPB 2 implementations discussed in this paper sends messages large enough to make use of this feature, however. The FT benchmark, which is currently undergoing revision, will make use of it.

The following software was used for the results presented in this paper:

```
IRIX version 6.12
MPI version 2.0
MIPSpro Fortran version 6.2
```

The compiler flag "-O3" was used for all compilations.

The nodes of the NAS cluster are always devoted to a single user job, so there is no contention for memory bandwidth with other jobs. In an SMP-based cluster, there is considerable freedom in how to arrange processors among nodes. Some of the competing considerations (for a fixed number of processors to be distributed over some number of SMP nodes) are:

1. Increasing the number of processors in a node to make use of low-latency communication within a node

2. Decreasing the number of processors in a node to reduce the effect of memory contention.

3. Using at least 1 fewer processes than processors on a node to avoid competition with system processes.

We have done some experimentation with different configurations. Unless otherwise noted, most reported results are the best obtained with several configurations. In section 6 we discuss the effects above in some detail.

4.3 Wright Laboratory Intel Paragon

Intel Paragon results were collected on the Intel Paragon located at the ASC Major Shared Resource Center (MSRC) X/PS-25 at USAF Wright Laboratories. It contains 368 compute nodes, 9 service nodes, and 24 multi-purpose I/O nodes. 352 of the compute nodes have 32 MB of memory, while 16 have 64 MB of memory. The machine has a 24-disk RAID system attached as a Parallel File System work area, with a total available space of 22 GBytes. All results were obtained from the General Purpose (GP) nodes. Each GP node has two i860/XP RISC processors: one processor is used for computation, the other for communication under OSF UNIX. Theoretical peak performance of the i860/XP GP node is 75 Mflop/s (double precision). (The Multi-Purpose (MP) nodes have three i860's and two can be used for computation under OSF UNIX.)

The nodes are connected by a network with the topology of a two-dimensional mesh. Messages are packetized and routed using dimension-order routing. Messages are automatically routed through intervening nodes without interrupting the processor. The network has a latency of 66 μs and a bandwidth of 70 MB/s for MPI messages.

The following software was used for the results presented in this paper:

```
OSF/1 Release 1.0.4 Server 1.4 R1_4 with Patch R1.4.1
MPI V1.0.12 external version - compiled with ch_nx lib
PG FORTRAN R5.0 Patch R5.0.3
```

The following compiler flags were used in compiling all of the NPB 2 codes:

```
-O4 -Knoieee
```

All runs were made under the Network Queuing System (NQS) where each node was dedicated to a single job with the -plk page lock flag. The only effect other batch jobs would have would be on the physical placement of processors and network contention.

4.4 JPL CRAY T3D

The CRAY T3D results were collected on the CRAY T3D SC256/264 at the JPL/ESS Parallel Computing Testbed. This T3D contains 256 DEC 21064 (Alpha EV4) processors. Each processor has a peak performance of 150 Mflop/s. The combined theoretical peak speed is 38.4 Gflop/s. Each processor has 64 MB of memory. Each processing element (PE) in the CRAY T3D system comprises the DEC Alpha microprocessor, local memory, and support logic. The PE is the basic computational unit in the CRAY T3D system's multiple instruction multiple data (MIMD) architecture. A CRAY T3D system node consists of two PEs sharing the switch and network support logic.

The PEs are connected by a bidirectional 3-D toroidal network. The hardware peak interprocessor communication rates are 300 MB/s in every direction through the torus, resulting in a bisection bandwidth of up to 76.8 GB/s.

The version of MPI supplied by CRAY originated from the Edinburgh Parallel Computing Centre version 1.5a with extensions. Its latency is about 37 μs, and its bandwidth is about 28 MB/s.
The following software was used for the results presented in this paper:

```
UNICOS 8.0
Cray CF77_M   Version 6.0.4.3 (6.62)
Cray GPP_M    Version 6.0.4.2 (6.17)
Cray CFT77_M Version 6.2.1.4  (281382)
```

The following compiler flags were used for all NPB 2.1 codes:

```
-dp -Wf-oaggress -Wf-onoieeedivide -C cray-t3d
```

and the following load options:

```
-Wl-Drdahead=on -C cray-t3d
```

All results were obtained either interactively or with NQS batch jobs. The nodes were dedicated to the benchmark run but there was a possibility of network contention with processes on other nodes.

5 Code Descriptions

5.1 Application Benchmark: LU

The LU benchmark solves a finite difference discretization of the 3-D compressible Navier-Stokes equations through a block-lower-triangular block-upper-triangular approximate factorization of the original difference scheme. The LU factored form is cast as a relaxation, and is solved by SSOR. The LU benchmark is based on the NAS NX reference implementation from 1991, but communication in the SSOR procedure has been considerably simplified.

The NPB 2 LU code requires a power-of-two number of processors. A 2-D partitioning of the grid onto processors is obtained by halving the grid repeatedly in the first two dimensions, alternating between x and y, until all processors are assigned, resulting in vertical pencil-like grid partitions. Each pencil can be thought of as a stack of horizontal tiles. The SSOR procedure is implemented as a generalized pipeline. Starting with the bottommost tile of a corner pencil, pointwise SSOR operations proceed along lines of the tile in the unit-stride direction, until all points on the tile have been relaxed. Neighboring tiles are sent updated values along adjacent edges, and these pencils can now process their respective tiles, while the first processor can now process points on the next tile above. Processing thus proceeds on a "hyperplane" of active tiles. The pipeline spends relatively little time filling and emptying and is perfectly load-balanced. Communication requirements are small compared to computation expense, making this parallel LU scheme relatively efficient. Cache line reuse in the relaxation sections is high.

5.2 Application Benchmark: SP and BT

Like LU, SP and BT use an implicit algorithm to compute a finite-difference solution to the 3-D compressible Navier-Stokes equations.

The solution is based on a Beam-Warming approximate factorization. The approximate factorization decouples the x, y and z dimensions, resulting in three sets of narrow-banded, regularly structured systems of linear equations that can be solved directly.

In SP, the flux Jacobians are fully diagonalized, and the resulting systems are scalar pentadiagonal (reflecting the presence of fourth order artificial dissipation) In BT, the resulting equations are block-tridiagonal (the fourth order dissipation appears only on the right hand side, so the left hand side difference stencil has a width of only 3), with (5×5) blocks. In both cases, the systems are solved using the Thomas algorithm - Gaussian elimination (GE), without pivoting, of a banded system. Parallelism in the solution phase appears both in the data (solutions along parallel grid lines can be computed independently, since they have been decoupled by approximate factorization) and through GE pipelining.

To solve these equations, both SP and BT use the multipartition [7] method. Each processor is assigned several non-overlapping sub-blocks (partitions) of points. This domain decomposition provides near-perfect load balance, requires only few data movements of moderate size along partition boundaries, and has no pipeline fill delay. Tradeoffs between this and other methods are described in [8].

Both SP and BT have two phases in each iteration. The first phase is the computation of the right hand side, which is identical in the two codes. It involves compact local difference stencils only. The matrix solution phases proceed as described above. The core of the SP solution phase is the solution of pentadiagonal systems using GE. There is very little data reuse. The core of the BT solution phase involves solution of (5×5)-systems of equations and multiplication of (5×5) matrices, both of which are part of the application of GE to the block-tridiagonal systems. There is significantly more data reuse in these operations.

Both the SP and BT codes require a square number of processors because of the decomposition requirements of the 3-D multipartition method. These codes have been written so that if a given parallel platform only permits a power-of-two number of processors to be assigned to a job, then unneeded processors are made inactive, but are counted when determining Mflop/s/process rates.

5.3 Kernel Benchmark: MG

The MG benchmark implements a V-cycle multigrid algorithm to solve the scalar discrete Poisson equation. This benchmark code is based on the 1991 reference implementation written by NAS. Four critical subroutines – the smoother, the residual calculation, the residual projection, and the trilinear interpolation of the correction – were optimized for both vector and RISC processors. These routines represent the vast majority of the total work. There are two different explicit smoothers used derived from trilinear finite elements. Most of these routines work well because they use continguous stride one memory access or, in the case of the smallest grids, the entire array fits in cache. This code requires a power-of-two number of processors. The partitioning of the grid onto processors occurs such that the grid is successively halved, starting with the z dimension, then the y dimension and then the x dimension, and repeating until all processors are assigned.

The MG benchmark pushes residuals and pulls solutions from dense to coarser grids and thus has short messages of different lengths based on the grid sizes.

6 Results

NPB 2 data can be used to examine a number of performance issues. In this report, we highlight a few of the more interesting results, using a single representative sample from a large number that could have been used. Detailed graphs of all NPB 2 results are available at http://www.nas.nasa.gov/NAS/NPB/NPB2Results/.

6.1 Performance per processor

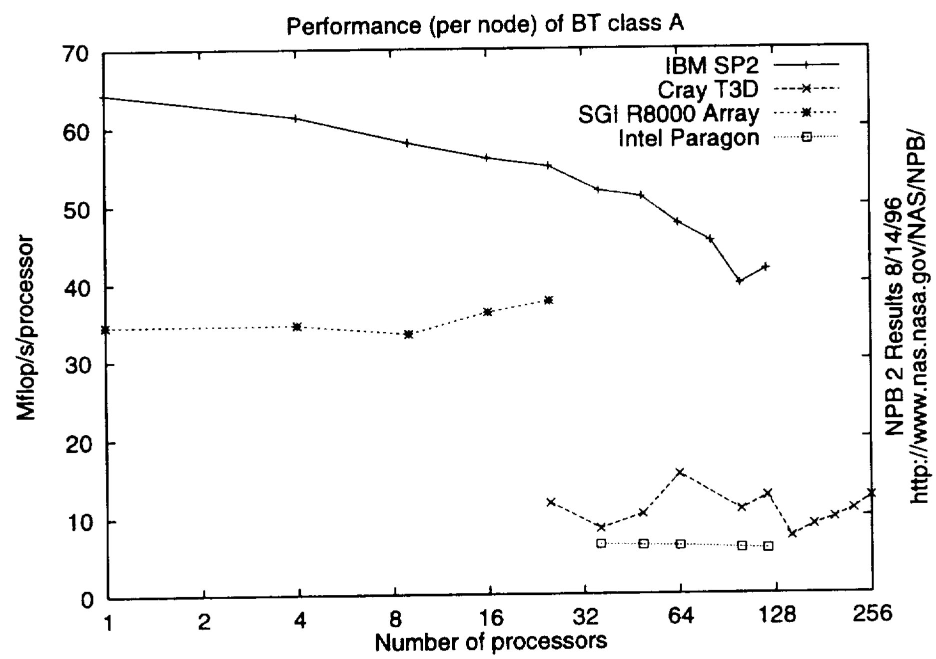

Figure 1: Per-processor Performance

Figure 1 shows the per-processor performance of BT class A on all machines. It shows a large disparity in per-processor performance between the four machines. The SP2 is the clear leader, obtaining as many as 65 Mflop/s/processor (but as few as 40 Mflop/s/processor on 100 nodes). The Power Challenge Array is a distant second with about 35 Mflop/s/processor. The T3D is substantially below that at about 10 Mflop/s/processor, and the Paragon registers barely more than 5 Mflop/s/processor. This ranking is consistent across all benchmarks.

The maximum Mflop/s/processor values obtained on each machine are:

```
SP2:        85 Mflop/s/process on MG class B 1 processor
PC Array:   46 Mflop/s/process on MG class B 1 processor
```

```
Paragon:      8  Mflop/s/process on MG class B 64 processors
T3D:          24 Mflop/s/process on LU class C 128 processors
```

We do not have at this point an explanation for why all machines except the T3D prefer MG.

The actual performance is not proportional to peak performance, which is:

```
SP2:        266 Mflop/s/processor   (66.5  MHz)
PC Array:   360 Mflop/s/processor   (90    MHz)
Paragon:    75  Mflop/s/processor   (50    MHz)
T3D:        150 Mflop/s/processor   (150   MHz)
```

We attribute the dominance of the SP2 to its high memory bandwidth. The other machines have far poorer memory bandwidth relative to peak performance. The SGI partially makes up for its poor memory bandwidth with its very large (4MB) secondary cache. We note that as of this writing, none of the above processors is state-of-the-art. The i860 is no longer produced, the Alpha 21064 in the T3D has been replaced by a a faster chip, the R8000 in the SGI Array will soon be superceded by the R10000, and the Power 2 multi-chip processor is now available with a higher clock rate.

We also note that performance of the SP2 falls off rapidly with number of processors. This is because its inter-node communication performance is relatively poor compared to its floating point performance. Fairly level lines for the Paragon and T3D out to 128 and 256 processors indicate good relative network performance. For the SGI Array, the maximum number of processors used was 32 spread over 4 nodes, so it was not possible to test scaling properties as much as on the other machines.

The sawtooth appearance of the T3D line results from the fact that a T3D may allocate only a power-of-two number of nodes. Thus, is is necessary to use 256 nodes when a problem requires only 144. The NPB 2 codes calculate per-processor performance on the basis of total allocated, not total used.

6.2 Total performance

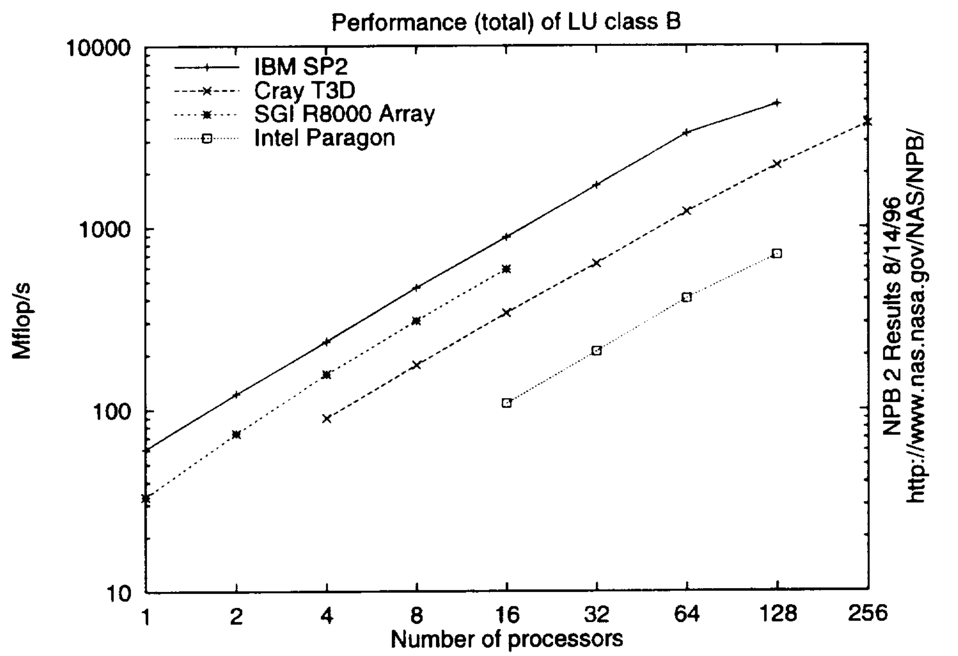

Figure 2: Total Machine Performance

Figure 2 shows total machine performance for LU class B. The information content is similar to that in Figure 1, except that it is easier to judge total machine performance. Among the machines we tested, the NAS SP2 still has the highest performance, even though it does not have as many nodes as the T3D or Paragon that were tested.

6.3 Efficiency

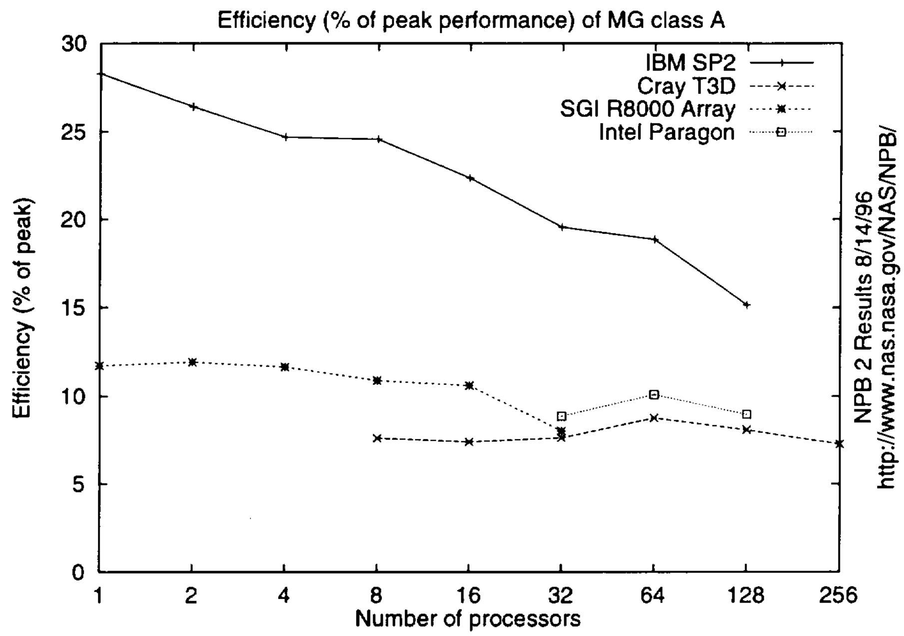

Figure 3: Machine Efficiency

Figure 3 shows the machine efficiency on MG class A. Efficiency is total Mflop/s divided by the peak Mflop/s, expressed as a percentage. The most interesting point of this graph is that it shows that the SP2 obtains its high performance not through high peak performance, but by attaining a relatively large fraction of peak performance - as much as 24of peak performance. This result emphasizes the inappropriateness of relying on peak performance to judge the capabilities of RISC-based machines. Though they are not represented here, vector machines typically attain a much higher percentage of peak performance on appropriate, well-written codes.

6.4 Performance as a function of problem size

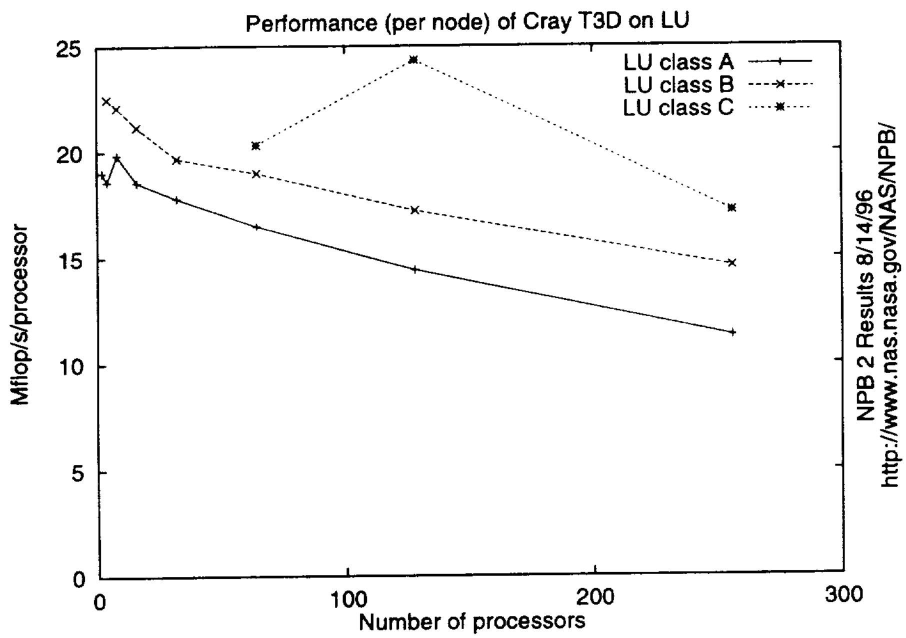

Figure 4: Performance of three classes of LU on the T3D

Figure 4 shows the performance of LU class A, B and C on the T3D. The largest size, class C, clearly performs the best on any given number of processors. We attribute this largely to the fact that the computation to communication ratio is highest, due to the best surface-to-volume ratio. A detailed analysis shows that this is not the only factor at work, as it does not exactly predict performance.

6.5 Differences in performance of different codes

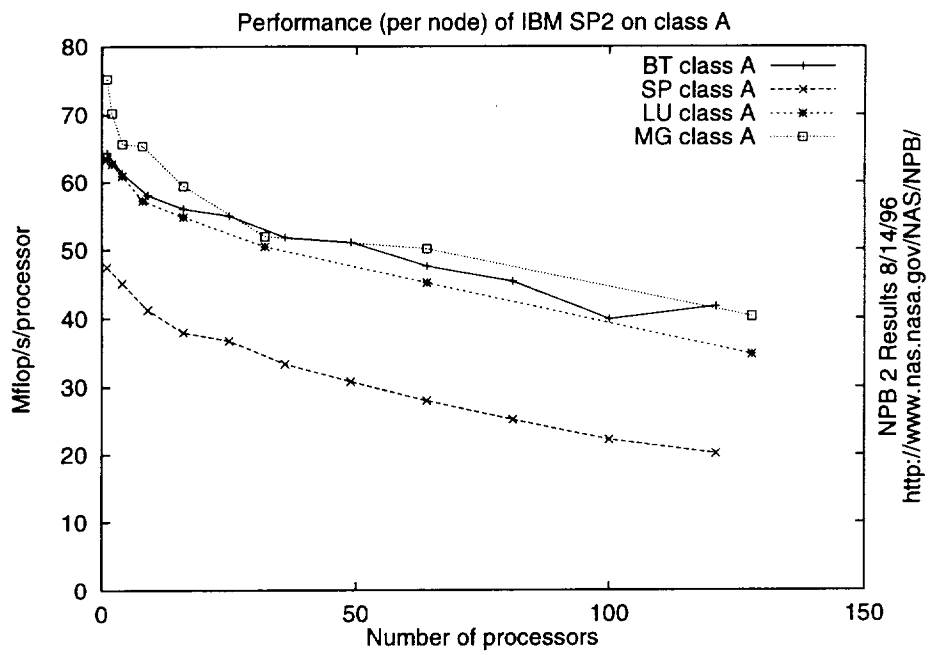

Figure 5: Performance of all Class A codes on the SP2

Not all NPB codes perform equally well. For instance, Figure 5 shows the performance of all class A codes on the SP2. MG, LU and BT have approximately the same performance, in Mflop/s, but SP exhibits substantially lower performance in Mflop/s/processor.

6.6 Comparison of NPB 2 and NPB 1 performance

It can be insightful to compare NPB 2 and NPB 1 results. While NPB 2 results can be reported in Mflop/s/processor, NPB 1 implementations may have different operation counts. Instead of Mflop/s/processor, we plot a the ratio of NPB 2 run time to the NPB 1 run time.

Because NPB 1 and NPB 2 data are not always available on the same numbers of processors, we calculate a ratio based on a fit of Amdahl's law to the NPB 2 results.

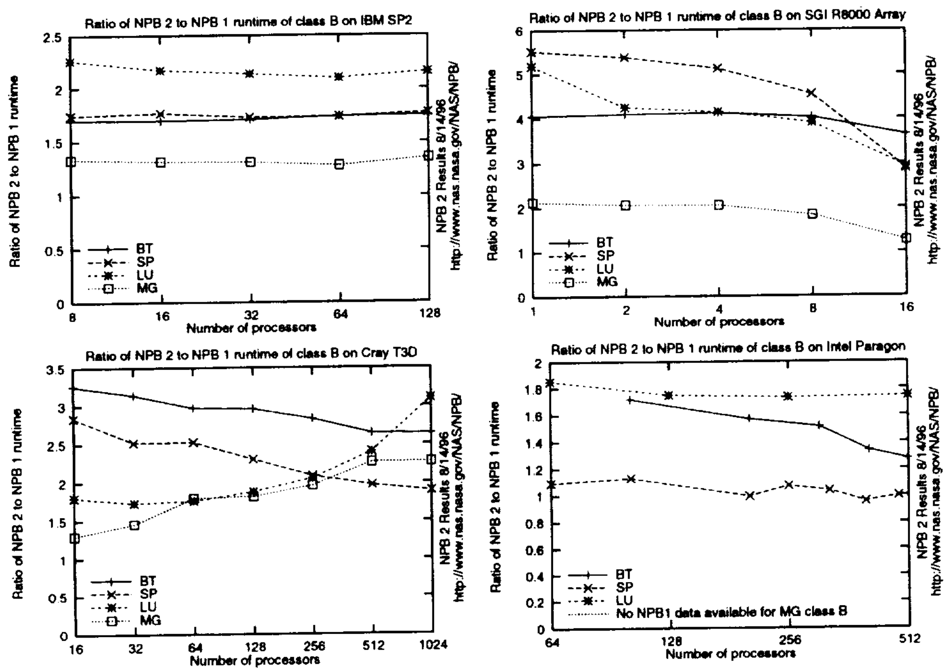

Figure 6: Ratio of NPB 2 to NPB 1 run time

Figure 6 shows the NPB 2 to NPB 1 run time ratio for all benchmarks on each machine. Higher numbers mean that NPB 1 performs better relative to NPB 2. Positive slopes show NPB 1 scaling better, and negative slopes show NPB 2 scaling better. Taking NPB 1 performance as the "peak achievable" performance, and NPB 2 performance as "normal" performance without a lot or architecture-specific tuning, we can make a statement about how much architecture-specific tuning is necessary to obtain high performance on each machine.

The Paragon has the smallest ratios between NPB 2 and NPB 1 performance. For the SP2 the ratio is usually between 1 and 2. For the T3D, NPB 2 performs relatively worse, between 1.5 and 3 times slower. The SGI Array results show the worst relative performance on NPB 2.

Taking this information together with the per-processor performance results, we conclude the following. The SP2 design makes it relatively easy to obtain a high percentage of peak performance. On the T3D and SGI it is much harder to achieve good performance, but careful architecture-specific tuning can improve the situation considerably. Architecture-specific tuning may buy you more on the SGI than on the T3D. Finally, the Paragon i860 nodes are relatively insensitive to tuning.

6.7 Discussion of clustered-SMP issues

The architecture of the SGI Power Challenge Array is quite different from the other machines that were tested, in that it is based on SMP nodes, rather than single processor nodes. In this respect, it is similar to many currently planned products from other companies.

In the earlier days of parallel computing, network topology could be quite important. For instance, communication patterns on a hypercube-based computer such as the Intel iPSC/860 had to take into account the topology of the network. On later machines, such as the SP2, the T3D and the Paragon, network topology effects still exist, but are usually much less important. They can often be considered "topology free", especially when there is an intelligent scheduler.

The Power Challenge Array may represent the first in a new generation of parallel computers and a return to the days when it mattered where processes were placed. There is non-uniformity both in the "network" (shared-memory communication has lower latency, lower point-to-point bandwidth, and higher aggregate bandwidth than inter-node communication) and the processors (two processes on the same SMP node may share a memory bus, competing for memory bandwidth, or may be on different nodes, with no competition for bandwidth). These two factors affect the configuration (optimal number of processors per node) and placement of processes on a set of nodes.

We note that a solely message-passing based code may not be the most efficient type of code on an SMP-based cluster. Indeed, it may be beneficial to use compiler-exploited parallelism within a node and MPI between nodes. While this may turn out to be an efficient model, it is not yet clear that it will be generally useful. For instance, compiler directives are not portable, and requiring the programmer to find two different types of parallelism may be unrealistic. There may be other reasons why such a program designed for such a system may not run well on a fully distributed system.

We obtained Array results for as many different configurations as were feasible. For instance, 16-process results were obtained for 16 processes on a single node, 8 processes on each of 2 nodes, and 4 processes on each of 4 nodes. The resulting data reflect a competition between reduced memory contention when spreading processes among nodes and reduced communication performance between nodes.

Some of the results of this experiment are summarized in table one. It is immediately evident that memory contention becomes an issue even at very small numbers of processors. For instance, one can usually obtain substantially better performance for an 16-process job by placing 8 processes on each of 2 nodes than by placing all 16 processes on a single 16-processor node. [2]

Table 1: Table 1. Mflop/s/process for different configurations

	bt.A	bt.B	lu.A	lu.B	mg.A	mg.B	sp.A	sp.B
16 procs x 1 node	18.5	13.8	39.7	29.0	17.8	19.2	27.7	14.2
8 procs x 2 nodes	32.1	26.9	33.9	34.1	29.6	31.9	35.6	26.5
4 procs x 4 nodes	36.2	31.2	37.8	36.7	38.2	39.9	37.4	N/A

7 Analysis/Conclusions

In this paper we have presented what we consider baseline NPB 2 results. All machines for which we have reported results have been or will soon be displaced by faster successors. We intend to track the performance of newer machines and report their performance in the same manner. It will also be interesting to see how much performance increase can be obtained at the 5% modification level allowed by the NPB 2 rules. It remains to be seen whether small changes to these portable codes can significantly increase performance. Vendors and others are encouraged to submit results.

The results shown here confirm several facts that are well known in the high-performance computing community: that actual performance on RISC processors is often around 10% of peak performance; that SP2 processors perform best and Paragon i860 processors (which are much older) perform worst; that careful architecture-specific tuning can improve performance significantly; that the SP2 has a relatively underpowered network.

[2]Note: 16 process cases run on 18-processor node
2x8 process cases run on 2 8-processor nodes
4x4 process cases run on 4 4-processor nodes

We have also shown that the NPB 2 suite can be used to make careful measurements of a single machine. In addition to the SMP cluster configuration analysis discussed in section 6, NAS has been using the NPB 2 suite for regression tests and the analysis of the effect of new system software on application performance.

By the end of 1996, we expect to release a complete set of NPB codes (including IS, CG, EP and a rewritten FT) as well as results for those codes.

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