Presented at the XV Internationl Conference of the Chilean Computer Science Society, Nov. 1995

Instruction level characterization of the Perfect Club programs on a vector computer *

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Abstract

In this paper we study the instruction level characteristics of the Perfect Club programs when compiled and executed on a vector processor. Using a trace driven approach we measure the degree of vectorization of the programs, the vector length used in operations, the operation type distribution, the basic block size and the balance between memory and compute operations. We also study the spill code introduced in the program by the compiler and the pressure on the dispatch unit of the vector architecture.

1 Introduction

Vector architectures have historically been evaluated using high level benchmarks. By high level benchmarks we understand measuring the performance of a vector machine using benchmarks like the PERFECT CLUB [1] or even LINPACK [2], that summarize the behavior of the machine in the total MFLOPS achieved. While these procedures certainly give some interesting information to the final user of the machine, they can not capture the performance advantages/disadvantages that each different vector architecture offers. We believe that a better approach to understand and characterize the behavior of a vector machine is the measurement of the low level (instruction level) activity of a collection of benchmarks.

While these approach has been routinely applied by the microprocessor community, there are very few studies of this kind in the vector computer arena. Microprocessor design is more and more driven by performance studies that try to identify all kinds of parallelism available in the instruction stream [3, 4, 5], and that evaluate possible bottlenecks in the architecture. The detailed knowledge of the relative frequency of execution of instructions [6, 7] leads to the inclusion of new compound operations (like the fused multiply add instruction) in the instruction set so that the "common case" is optimized and executes in fewer cycles. On the other hand, vector machines tend to offer more power by moving into the multiprocessor world and by reducing cycle time, but the basic architecture of the vector processor has not changed very much since the introduction of the Cray-1 [8]. Moreover, as CMOS technology continues advancing, the cycle time difference between expensive ECL vector supercomputers and low-cost microprocessors is getting smaller and smaller. Thus, it won't be possible to sustain the performance advantage of vector computers solely on the cycle time. Future vector architectures will have to make as much use as possible of the instruction level parallelism found in scientific programs. New designs will have to borrow as many techniques as possible from the superscalar world, and mixed designs with an off-the-shelf superscalar microprocessor tightly coupled to a vector cpu will become more common. Vector cpus will have to deal with out-of-order execution, schemes to reduce the register pressure and an increase in the number of computational functional units. In order to evaluate the tradeoffs involved in all these architecture features, the instruction-level behavior of programs has to be measured. In [9, 10] the Cray-YMP [11] architecture is evaluated through a study of the scalar and vector instruction level

*This work was supported by the Ministry of Education of Spain under contracts TIC 880/92 and 0429/95, by ESPRIT 6634 Basic Research Action (APPARC) and by the CEPBA (European Center for Parallelism of Barcelona).

characteristics. In [12, 13] detailed measuring models of vector architectures are presented. In [14] a study of the Cray-YMP vector register usage was carried out and several alternative vector register configurations were proposed. Nevertheless, there are few studies that measure the relative importance of vector instructions, the frequency of stalls, or the instruction level parallelism.

This paper will present data on the instruction level characteristics of the thirteen PERFECT CLUB programs when compiled using a production vector compiler. We have implemented a tracing tool called Dixie [15] able to generate a detailed instruction level trace of all the program execution (including user plus library code). With this tracer we are able to measure at a fine level the degree of vectorization of the programs, the vector length used in operations, the operation type distribution, the basic block size and the balance between memory and compute operations.

The structure of this paper is as follows. Next section will present our measurement technique. Section 3 and 4 will present the basic operation counts for the benchmarks. Section 5 will present the vector length distribution of the programs. Section 6 will look at the spill code generated by the compiler. Section 7 will present measurements on the pressure on the dispatch unit. Finally, in section 8 we will present our conclusions.

2 Overview of the measurement technique

We have taken a trace-driven approach to gather all the data presented in this paper. We have developed a pixie-like tool called Dixie that is able to produce a trace of basic blocks executed as well as a trace of the values contained in the *vector length* (`vl`) register. The ability to trace the value of the *vector length* register is critical to have a detailed simulation of the program execution, since each vector instruction can execute with a potentially different vector length. Thus, our measurements do not suffer from the problems reported in [10].

Dixie has been targeted to a Convex C3480. This machine is a vector multiprocessor with 8 processors. Each individual processor has a scalar and a vector unit. The vector unit consists of two functional units (one is fully general purpose and the other only performs add-like operations) and one memory accessing unit. All these functional units are connected to a single vector register file which is organized in banks. It has 4 banks which hold 2 vector registers each. The vector registers hold 128 elements of 64 bits. Each bank has 2 read ports and 1 write port. The machine implements fully flexible chaining [16] except for loads, which can not be chained to a computation instruction. See [17] for further details. We have compiled all the *Perfect Club* benchmarks using the fortran compiler (*Convex FC version V8.0*) with optimization level -*O2* (which implies vectorization). Then, the output of these compilations are fed into Dixie which produces 1) a modified executable file with instrumentation code that will generate a trace and 2) a basic block description file that maps basic block identifiers to the actual instructions of each basic block. When you run the instrumented executable it generates a trace of basic block identifiers and a trace of every value that is assigned to the vector length register. This two parallel traces are consumed by a cycle-level simulator that uses the basic block description file to simulate the execution of every single instruction and measure the dynamic behavior of the program. Each time the simulator finds an instruction that loads the `vl` register it will consume a value from the vector length trace. Dixie is able to trace user and library code and, thus, the simulation runs include the user vector code plus all the vector code found in the fortran math libraries. It is important to note that we simulate the output of a commercial compiler without introducing any modification in it and that this tracing method gives a high precision in all of our measurements.

3 Basic Operation Counts

Table 1 presents the basic operation counts for the thirteen programs of the Perfect Club. First column in this table presents the total number of basic blocks (in millions) executed for each program. Next two columns present the total number of instructions issued by the dispatch unit, broken down into scalar and vector instructions. In this paper we will distinguish between *instructions* and *operations*. A scalar instruction performs a single operation, while a vector instruction performs a varying number of operations, depending on the value of the vector length (`VL`) register. Column four presents the number of operations performed by the vector instructions (note that the scalar operation counts are identical to the scalar instruction counts). Fifth column is the percentage of vectorization of each program. We define the degree of vectorization of a program as the ratio between the number of vector operations and the total number of operations performed by the program (i.e., column four divided by the sum of columns two and four). Finally column six presents the average vector length used by vector instructions, and is the ratio between vector operations and vector instructions (columns four and three, respectively).

What can be seen for table 1 is that the thirteen programs have wildly different characteristics, ranging from programs that are almost fully vectorizable, like ARC2D, to programs that exhibit almost no vectorization at all (SPICE). All tables that will be presented in this paper have been sorted following the degree of vectorization column in table 1. We have found this measure very useful in classifying the programs into distinct categories. In fact, the degree of vectorization measured in terms of operations is more accurate than other indirect measures of vectorization such as speedup. We have the execution time of the thirteen programs when run in vector mode and scalar mode, and have found that the associated speedup does not have a good correlation with the degree of vectorization. For example, both OCEAN and DYFESM show a speedup of 1.2 when run in vector mode with respect to its scalar version on a single processor of the C3480, and, nonetheless, they have very different degrees of vectorization (24.7% for OCEAN and 74.7% for DYFESM). This suggests that DYFESM is experiencing some problem when run on the C34 architecture, but that it's a good candidate to obtain better speedups on some other vector architecture. Thus, we will use the degree of vectorization in terms of operations as our main measure of vectorization ratio. Table 1 is divided in three regions. The top six programs are programs that should execute efficiently on vector architectures, given that they have a degree of vectorization over 70%. This group of programs will are referred as the "highly vectorizable" set of programs. The next three programs, MG3D, MDG and ADM, are the medium vectorized codes. They have approximately 50% of all its operations executed in vector mode, but, as Amdahl's law shows, their performance on a vector architecture will be not only determined by the vector portion of the codes but also by the scalar instructions. Thus, these programs have a theoretical maximum speedup of 2, since even if the vector portion could be executed in negligible time, the scalar portion would still take a substantial amount of time. Finally, the last four programs represent a class of programs that are not expected to benefit when executed on a vector architecture.

Another interesting point from table 1 is the average vector length observed in the programs (section 5 will present more detailed data about vector lengths). Even for the highly vectorizable subset of programs, the average vector length is not very high. Note that the C34 has a maximum vector length of 128 elements. Only ARC2D and BDNA get somewhere close to having a 100 elements on average, with the rest of programs (FLO52, TRFD,DYFESM and SPEC77) having very small vectors (less than 64 elements). In [1] it is reported that the data sets distributed with the Perfect Club benchmark are not very large in order to allow these programs to run on a wide variety of computers, ranging from workstations to supercomputers. This explains why the observed vector lengths are small, since a data set suited for a vector supercomputer would take too long to be run on a workstation.

In table 2 we have included the basic operation distribution for the six programs selected. We have classified all operations executed by each programs in two major groups (Vector and Scalar) and each group has been further broken down into a total of four categories. These four categories are: Load, Store, Mul and Add operations. In the vector group, the Load and Store categories include, respectively, the gather and scatter instructions. The Mul category includes all types of instructions that can only be executed on the general purpose functional unit, that is, includes all multiplications, divisions and square roots. The Add category includes all other arithmetic operations not included in the Mul category, that is, adds, subtracts, logicals, shifts, etc.

What can be seen from table 2 is that all the programs under study are memory bound when run on an architecture like the C34, having only one memory bus and two functional units. Since we only have one memory port, all operations listed under columns Load and Store will use the same hardware resource, while operations listed under columns

Mul and Add can potentially run in parallel. For the highly vectorizable set of programs, it is interesting to note that the scalar portion of the code is clearly much smaller than the vector portion. The total number of memory accesses performed in scalar mode is not very high, and, usually the majority of the scalar code are instructions in the Add category. This is not surprising, since the scalar code present in vector codes is mainly support code. That is, the scalar code found in vector loops is mostly composed of address computations (additions and shifts) and loop control instructions (decrements and comparisons).

The situation is very different for the medium and low vectorizable set of programs. For these seven programs, the scalar portion of the code is important. Moreover, since a high part of the program's computations are performed in scalar mode, we have an increase in the total number of operations of categories Mul and Add.

4 Operation Frequency

To better understand the distribution of instructions performed by the thirteen programs, we have further classified all vector operations into 11 subsets. Table 3 presents this classification. We have taken all vector operations for each program and classified them between memory and compute operations. The compute operations appear in columns 2 to 8 in table 3, under the label "Compute". The memory operations appear in columns 9 to 12 under label "Memory". The first column of the table is the total number of operations (in millions) performed by vector instructions (and is the same as the fourth column in table 1). All the other columns are percentages taken over this first column, and thus, columns 2 to 12 add up to a 100%.

In the compute category, we have distinguished between seven types of operations. The two most common operations are additions and multiplications (subtractions are included in the "+" category). As it can be seen, almost all programs have a 90% of its compute operations split between additions and multiplications. Overall, additions and multiplications appear to be in 1 to 1 proportion. Five programs (ARC2D, DYFESM, SPEC77, OCEAN and TRACK) have slightly more multiplications than additions while the rest present the opposite case. This result suggests that in order to have a well balanced architecture (at least in terms of functional units), the number of units able to perform a multiplication and the number of units able to perform add-like operations should be the same.

The other types of compute operations are much less frequent. Nevertheless, it is very interesting to see in table 3 the percentages for high-cost operations like division and square root. Most usually, hardware implementations of division and square root are not full pipelined, and thus, may require a high number of cycles between consecutive dispatching of the same operation. For example, consider that a square root requires 20 cycles to complete and that it is not pipelined (that is, a second square root operation will have to wait the full twenty cycles before starting. Then, for example, the importance of the 1.10% of square root operations performed by BDNA is automatically multiplied by 20, since each individual square root operation costs the same as, say, performing 20 simple additions. Thus, the percentages represented in columns 4 and 5 would become much more important.

Under columns labeled $\prod$ (prod) and $\sum$ (sum) we have included the frequency of operations performed using the reduction operators available in the C34 architecture. In terms of operation complexity, the prod and sum operators are very similar to the multiplication and addition operations. The major difference is that these reduction operations have a higher latency since they have to retrofit its own results into the adder/multiplier in order to perform the full reduction. From table 3 it is clear that the prod operation is seldom found in the Perfect Club programs while the sum operation can be quite important in some programs (MDG 15.97 %, SPEC77 7.37% and DYFESM 5.98%) and appears in almost all the rest (ARC2D, FLO52, BDNA, ADM, OCEAN and TRACK).

In the memory category, we have include vector loads and stores as well as the indirect memory accessing functions, gather and scatter. With respect to loads and stores, we have that overall there is a 52% more loads than stores. It has already been reported for scalar programs [6] that it is more common to have load instructions than store instructions. Also in [9] a similar relation was found for code compiled on a Cray Y-MP vector multiprocessor. It is interesting to note that for all programs the percentage of store operations

Program	#bbs	#insns S	#insns V	#ops V	% Vect	avg. VL
ARC2D	5.2	63.3	42.9	4086.5	98.5	95
FLO52	5.7	37.7	22.8	1242.0	97.1	54
BDNA	47.0	23.9	19.6	1589.9	86.9	81
TRFD	44.8	352.2	49.5	1095.3	75.7	22
DYFESM	34.5	236.1	33.0	696.2	74.7	21
SPEC77	166.2	1147.8	262.6	3337.8	74.4	12
MG3D	452.14	11066.75	663.79	17995.49	61.9	27
MDG	185.90	4446.64	746.97	5611.66	55.8	7
ADM	42.4	709.0	104.3	694.8	49.5	6
OCEAN	165.64	4414.30	16.17	1444.92	24.7	89
QCD	80.05	1079.77	4.10	91.84	7.8	22
TRACK	50.67	505.96	4.47	26.96	5.1	6
SPICE	31.12	279.06	3.37	7.80	2.7	2

Table 1: Basic operation counts for the Perfect Club programs.

	Types of operations							
	Vector				Scalar			
Program	L	S	*	+	L	S	*	+
ARC2D	1364.6	565.3	1247.3	909.3	23.3	5.9	0.9	29.1
FLO52	469.3	222.1	228.7	321.9	9.7	5.1	0.3	17.8
BDNA	408.5	292.2	383.4	505.9	65.5	28.9	28.8	99.0
TRFD	433.0	224.3	216.8	221.2	122.20	47.0	0.8	151.8
DYFESM	289.7	108.2	149.7	148.6	74.8	29.8	1.8	106.3
SPEC77	1054.0	442.0	813.0	1028.8	283.2	137.2	18.5	565.8
MG3D	4575.67	4052.69	4145.48	5221.65	4713.00	2513.26	33.77	3406.22
MDG	923.94	650.04	782.93	3254.75	1473.82	723.74	215.68	1888.52
ADM	221.5	135.0	155.2	183.0	234.2	114.0	40.9	285.3
OCEAN	491.55	493.53	233.40	226.44	919.33	856.44	433.03	2044.65
QCD	45.26	42.99	0.01	3.59	350.73	156.90	120.06	380.22
TRACK	10.80	7.82	4.79	3.55	186.39	74.68	33.21	162.07
SPICE	3.61	2.36	0.71	1.11	98.99	38.48	12.69	102.49

Table 2: Balance between Vector and scalar operations.

remains between a 10% and a 20%, except for OCEAN and QCD where this percentage is substantially higher. In the case of QCD, for example, it was found that most of the vector code is in loops used to copy/move data from one data structure to another and, consequently, the number of vector loads and stores is almost the same.

5 Vector Length Distributions

A very important factor in achieving high performance in vector execution is the effective vector length used by vector instructions. Current vector architectures have very different sizes for its vector registers, ranging from 64 elements in Cray-YMP, to 128 elements in YMP-C90 and Convex C3 and up to 8192 elements in the reconfigurable vector register file of Fujitsu's VP2400/10 machine. The higher the number of register elements used during the computation the better, because memory and functional unit latencies and vector start-up costs are amortized over the length of the vector register. Longer vector lengths have a lower associated overhead and, thus, achieve higher performance.

We have monitored every single value stored in the vector length register of the Convex C3 machine. Recall that this machine has a max-

	Total	Compute							Memory			
Program	($\times 10^6$)	$+/-$	$\times$	$\div$	$\sqrt{}$	$\prod$	$\sum$	other	LD	ST	gath.	scatt.
ARC2D	4086.51	19.89	28.53	1.56	0.44	0.0	0.13	2.23	29.30	13.83	4.09	0.0
FLO52	1242.01	24.06	15.99	2.33	0.09	0.0	0.10	1.77	37.78	17.88	0.01	0.0
BDNA	1589.94	24.69	21.63	1.38	1.10	0.0	1.42	5.71	25.50	18.38	0.19	0.0
TRFD	1095.33	19.86	19.73	0.07	0.0	0.0	0.0	0.33	39.53	20.48	0.0	0.0
DYFESM	696.2	15.34	21.51	0.0	0.0	0.0	5.98	0.03	40.77	15.55	0.83	0.0
SPEC77	3337.83	21.12	23.78	0.57	0.01	0.0	7.37	2.35	31.57	13.24	0.01	0.0
MG3D	17995.49	28.86	21.97	1.07	0.00	0.00	0.00	0.16	25.43	22.52	0.00	0.00
MDG	5611.66	15.42	12.82	0.88	0.26	0.00	15.97	26.61	16.46	11.58	0.00	0.00
ADM	694.77	23.34	19.24	3.00	0.11	0.00	0.86	1.53	31.88	19.44	0.00	0.00
OCEAN	1444.92	10.73	14.13	2.02	0.00	0.00	0.42	4.52	33.97	34.16	0.05	0.00
QCD	91.84	3.88	0.01	0.00	0.00	0.00	0.01	0.01	49.28	46.80	0.00	0.01
TRACK	26.96	9.39	13.58	4.18	0.00	0.00	3.03	0.74	40.05	28.93	0.00	0.09
SPICE	7.80	14.27	0.00	9.08	0.00	0.00	0.00	0.01	46.35	30.29	0.00	0.00

Table 3: Breakdown of Vector operations in the Perfect Club programs. Column Total is in millions of operations. Rest of columns are percentages over column Total.

imum vector length of 128. The accumulated percentage distribution of all the values gathered is plotted in figure 1. This curve is labeled DEFINED. We have also computed a weighted version of this distribution that corresponds to weighting the percentage of times that each vector length is defined by the number of vector instructions that will actually use that vector length. This second curve is labeled USED.

From figure 1 what is clear is that the vector length distributions do not follow any regular pattern. Note that most programs have almost all their vector lengths lower than 64 (SPEC77, TRFD, DYFESM, MDG, QCD, TRACK and SPICE). Moreover, the total percentage of instructions executed using a vector length of 128 is not very high. Except in ARC2D, BDNA and OCEAN the rest of programs have a very small percentage of instructions using a vector length of 128. For the USED vector length distribution there is a 29.4% of vector instructions executed that use a vector length lower or equal than 3. There is even a 7.3% of vector instructions executed with a vector length equal to 0. This is a surprising but not impossible vector length since there are many vector lengths that are computed at runtime and may turn out to be very small or even 0. The majority of vector instructions (79.3%) are executed with a vector length lower or equal than 16. The median of the vector lengths used is between 13 and 14, with $vl = 14$ being a rather special value since there are 43% of all vector instructions executed with this vector length. This is due to a particular routine (CSHIFT in MDG) being very heavily executed.

All in all, this data suggests that the vector registers of the C34 machine are heavily underutilized. Next section will discuss in more detail what could be a better choice for the length of the vector registers.

5.1 Full Stripes

Given the results presented in the previous section, we want to investigate what would be a reasonable value for the length of the vector registers. What we have done is compute the percentage of times that a vector register is used in all its capacity (we term this situation as a "full stripe"). For example, say a program has two vector instructions, and that the first instruction uses a vector length of 128 and the second one a vector length of 72. If we consider the vector register size to be 128, we have that a 50% of all instructions have used full stripe. Now, if we consider a vector register size of 64 elements, it is clear that the same two instructions would have to execute twice in order to get all their work done. The first instruction would "translate" into two instructions that would operate on 64 elements each one. The second instruction would turn into two instructions also, but that would operate on 64 and 8 elements respectively. Thus, if we had a vector register of 64 elements, 3 out of 4 instructions (75%) would be using a full stripe.

Figure 2 presents the percentage of full stripes of each program, considering four pos-

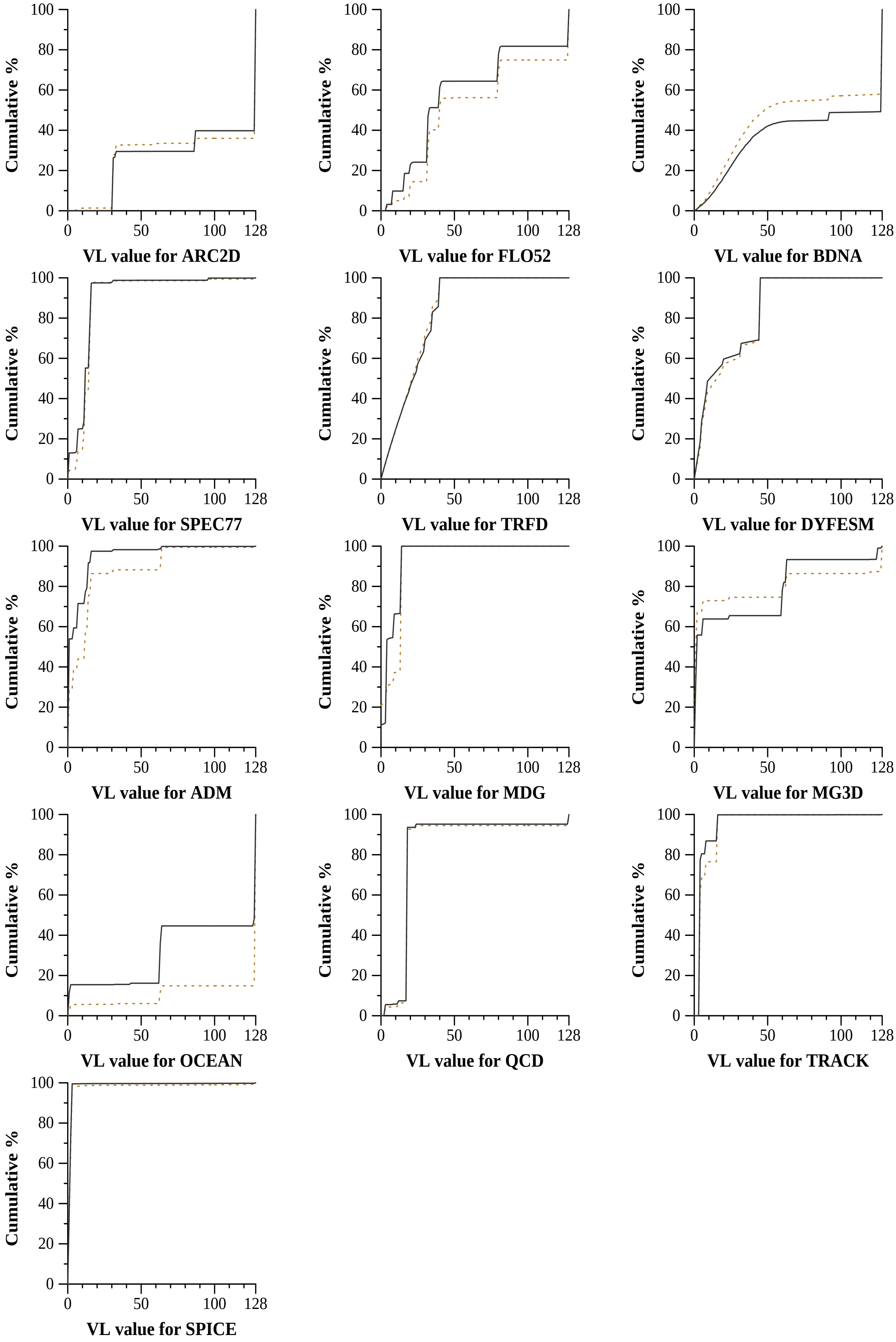

Figure 1: Distribution of the VL values for the Perfect Club programs

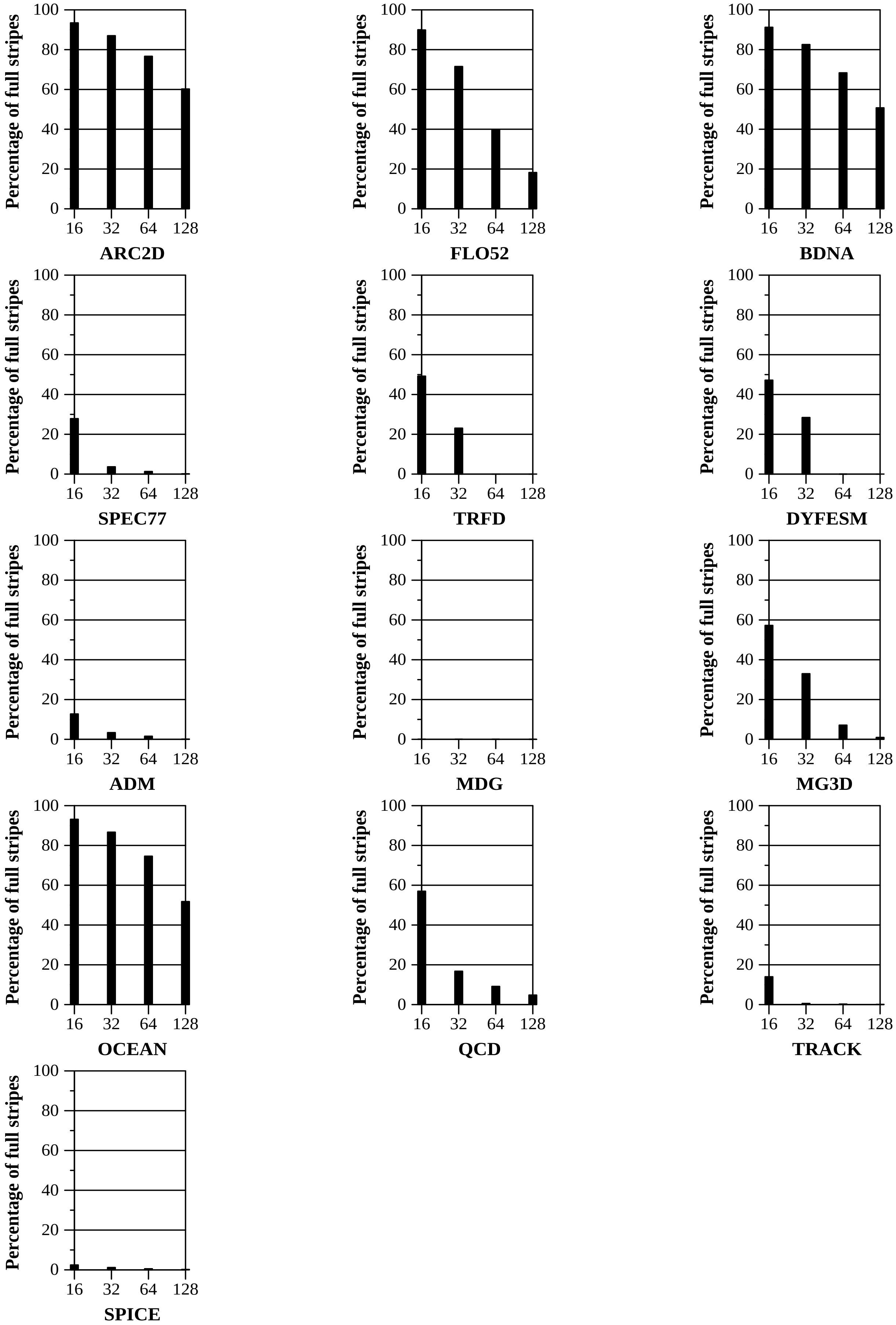

Figure 2: Percentage of full stripes for different vector register sizes

sible values for the vector register size: 16, 32, 64 and 128 elements. For example, the figure shows how in BDNA 60% of all executed vector instructions used a vector register of size 128. For the same program, if the vector register size was 16 elements, almost 92% of all vector instructions would fully use the vector registers.

From figure 2 we can see that in order to augment the percentage of full stripes we would have to choose a relatively small vector register size. The average vector length used in vector operations is around 21 which indicates a rather poor usage of the vector registers, although variability is high (standard deviation from the mean is 30.7, which represents a c.o.v.[1] of 1.4). Figure 2 shows how for the vectorizable subset of programs a good value for the register size could be 32 elements, since with this value we would be executing full stripes in almost the 80% of cases.

It is important to note that in [1] it is reported that the data structures found in the programs of the Perfect Club were artificially reduced to make sure that the benchmark could be executed on a large range of machines, and thus, they do not truly represent the problem sizes usually found in supercomputer's applications. Therefore, we will not draw from the data presented in this section and in the previous section very strong conclusions due to the fact that the vector length distribution could be significantly different for other vector workloads.

6 Spill Code

Another interesting aspect of vector processors is the usage of the vector register file. Since each vector register in a vector processor has a long size, the total amount of vector registers that can be implemented in a vector architecture is not very high. The C34 and the CRAY Y-MP, for example, only have 8 vector registers. This limited number of registers makes very difficult the task of the compiler, since it has to balance aggressive scheduling techniques against a very limited number of vector registers. When compiling large dependence graphs, the register allocator usually runs out of available free registers and has to spill some live variables to the stack and later reload them. This spill code will be very negative in an architecture where there is only one memory bus. Every spill load/store instruction inserted by the compiler will result in a net increase of total memory traffic. Since we already saw in section 3 that the benchmark programs are memory bound, this net increase in memory traffic will most probably not be hidden by other computations and will result in a decrease in performance.

The compiler used to compile the Perfect Club codes puts all its spill code on the stack, and seldom ever uses the stack to hold vector data that it is not spill data. Thus, we have been able to distinguish spill memory operations from "normal" memory operations by checking if the memory access was to the stack or not. We have further enhanced our technique to detect spill code by creating a table (at runtime) of all data that is stored to the stack and checking that there is some load that later reloads it. If this is the case, then we annotate that both the store and the load were spill operations. If, by chance, there is a load or a store that references the stack but it is not in our table, this memory access is not considered to be spill code.

Using this technique, the total number of vector spills has been computed for each program. Table 4 presents the results (all data is in millions of operations). Under column LD we have the total number of non-spill load operations performed in vector mode. Under "spill-LD" we have the total number of spill load operations performed in vector mode. For example, BDNA has more spill loads than normal loads, since it performs 265 millions of spill-loads and only 142 millions of normal loads, which represents a $(265 \div (265 + 142))$ 65% approximately of spill-loads.

It is interesting to note that for the vectorizable programs the percentage of spill is rather remarkable. Considering loads and stores together, ARC2D has a 12.2%, FLO52 a 11.9%, and BDNA 69.5%. The case of BDNA is clearly surprising. We have investigated this molecular dynamics code and found that it has extremely long loops (in one case, a single loop turned into more than 700 vector instructions!). These extremely long loops run out very fast of registers, and the code is constantly spilling registers to memory. All in all, the influence of having only eight registers in a single bus architecture is quite evident. All the spill code presented in table 4 will impact (negatively) the run time of the programs

[1] coefficient of variation.

Program	Vector load ops			Vector store ops		
	LD	spill-LD	%	ST	spill-ST	%
ARC2D	1242.91	121.67	8.92	478.54	86.79	15.35
FLO52	428.15	41.13	8.77	181.00	41.13	18.51
BDNA	142.47	265.99	65.12	71.30	220.88	75.60
TRFD	432.96	0.00	0.00	224.31	0.00	0.00
DYFESM	289.19	0.47	0.16	107.77	0.47	0.43
SPEC77	1030.19	23.81	2.26	419.64	22.32	5.05
MG3D	4575.67	0.00	0.00	4052.69	0.00	0.00
MDG	923.94	0.00	0.00	650.04	0.00	0.00
ADM	202.49	19.00	8.58	116.05	19.00	14.07
OCEAN	491.55	0.00	0.00	493.53	0.00	0.00
QCD	45.26	0.00	0.00	42.99	0.00	0.00
TRACK	10.80	0.00	0.00	7.82	0.00	0.00
SPICE	3.61	0.00	0.00	2.36	0.00	0.00

Table 4: percentage of spill code in vector memory operations. Columns 2, 3, 5 and 6 are in millions of operations.

7 Pressure on the dispatch unit

A very interesting property of vector architectures is that they can potentially achieve the same amount of instruction level parallelism as superscalar architectures using a much simpler decoding hardware. Superscalar architectures have to explore a "window" of ready instructions to try to find independent instructions and dispatch them. On the other hand, vector processors simply issue instructions in a sequential way but, since each vector instructions implies a lot of operations, each vector instruction runs for a long period of time. When the vector processor issues two vector instructions, it has two functional units busy at the same time, much as a superscalar processor does, but with a much smaller effort in terms of instruction bandwidth and dispatch logic.

To get an insight into the amount of work that the dispatch unit of a vector processor has to do per cycle, we have taken the following approach. First, we compute a lower and an upper bound of the execution time of each program (in this section we understand "execution time" as "number of cycles executed"). As a lower bound of the number of cycles that a program will execute, we use tables 1 and 2 to compute which resource in the architecture is the resource most used. For example, for program ARC2D, the memory bus is the most used resource, and, in particular, it is used to perform 1929.91 millions of "transactions". This number is the sum of all vector loads and vector stores, and does not include the scalar memory operations. We de not include the scalar memory operations because we are computing an optimistic lower bound and thus we assume that all scalar memory operations hit in the cache. As another example, for program OCEAN, the most used resource is the dispatch unit itself, since the program has a total of 4430 millions of instructions to dispatch and all the functional units of the architecture execute less operations (the adder in the scalar unit performs 2044.65 millions of operations, for example).

As an upper bound to the execution time of the program, we take the sum of all its operations. We consider this value to be an upper bound because it is unlikely that the program has no instruction level parallelism at all, and, thus, it is likely that it can overlap some computations with others.

With this two bounds, presented in columns 1 and 2 in table 5, and knowing the total number of instructions issued by the program (column 3 of table 5), we can compute the ratio of instructions per cycle that have to be dispatched by the control unit. By dividing the lower bound of execution time by the number of instructions in the program we obtain an upper bound on the issue ratio. Similarly, by dividing the upper bound of execution time by the number of instructions in the program we obtain a lower bound on the issue ratio. This bounds can be seen in columns four and five of table 5.

Program	cycles (lower bound)	total ops.	total insns	(1)/(3)	(2)/(3)
ARC2D	1929.91	4149.84	106.25	18.2	39.1
FLO52	691.41	1279.71	60.49	11.4	21.2
BDNA	700.63	1828.81	258.47	2.7	7.1
TRFD	657.27	1447.56	401.78	1.6	3.6
DYFESM	397.89	932.38	269.09	1.5	3.5
SPEC77	1495.96	4485.64	1410.39	1.1	3.2
MG3D	11730.54	29062.23	11730.54	1.0	2.5
MDG	5193.61	10058.30	5193.61	1.0	1.9
ADM	813.31	1403.77	813.31	1.0	1.7
OCEAN	4430.47	5859.22	4430.47	1.0	1.3
QCD	1083.86	1171.61	1083.86	1.0	1.1
TRACK	510.43	532.92	510.43	1.0	1.0
SPICE	282.43	286.86	282.43	1.0	1.0

Table 5: Pressure on the dispatch unit. First column is an ideal lower bound on the number of cycles needed to execute each program. This lower bound is computed for an hypothetical vector architecture that had one Load/Store bus, one adder, one multiplier and a pipelined scalar unit. The bound can be derived from the last eight columns of table 1.

Table 5 shows how the subset of highly vectorizable programs does not have very tight bounds. For example, in the worst case, ARC2D has to dispatch 1 instruction every 18 cycles. Clearly this does not represent a very high pressure on the dispatch unit. Nevertheless, as the vectorization ratio decreases, the programs start to increase their instruction fetch/dispatch bandwidth. The lower seven programs in the table will clearly need a fast control unit to avoid wasting many cycles. These seven programs will be negatively affected by delay cycles introduced by jumps and i-cache misses, for example. The table also shows the great advantage of vector execution against superscalar execution. For vector programs, the control unit has many cycles where it is idle, and can use them to implement techniques that improve overall performance (branch prediction, out-of-order execution, etc.) at a low cost. These techniques are usually costly in superscalar processors because they have to be implemented (usually) in a single cycle and, thus, can negatively affect the cycle time of the processor. On the other hand, on a vector architecture the same techniques could be implemented without necessarily having to being done in a single cycle.

8 Conclusions and Future Work

In this paper we have used a trace driven approach to gather data about the instruction level characteristics of vector programs. Our method has given us the full execution of the programs, including not only user code (like in many of the instruction level studies found in the literature) but also the library code with all the specific fortran math vector routines.

Using these traces we have presented the degree of vectorization in terms of operations of all the Perfect Club programs. We have seen how the proportion between compute and memory operations is almost 1 to 1. We have also seen how the effective vector length used in the operations is rather low, around 21, which indicates that much of the register space is being wasted and, therefore, the startup overhead of vector operations is not being compensated along the full length of the vector. From the operation type distribution we have concluded that the two most important computation instructions are additions and multiplications (80% of all computation operations) and that they appear with almost the same frequency. Thus, designs that have a good balance between the number of units that perform additions and the number of units that perform multiplications will better match the behavior of the programs.

We have examined the amount of spill code and have found that for the vectorizable set of programs it was quite high. Since the architecture under study is single-ported to memory, we conclude that this spill will have a clear negative effect on execution time. We have also looked at the pressure on the dispatch unit. We have found that for the non-vectorizable set of programs, a dispatching of one instruction per cycle is needed. On the other hand, the vector programs can spend a mean of 18 cycles between instructions without requiring the intervention of the dispatch unit.

The data presented in this paper will be used to study new alternative vector architectures that better match the characteristics of vector programs. We are currently investigating using decoupling techniques to reduce the imbalance between memory and compute operations detected.

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