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An Experiment to Measure the Usability of Parallel Programming Systems

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SUMMARY

The growth of commercial and academic interest in parallel and distributed computing during the past fifteen years has been accompanied by a corresponding increase in the number of available parallel programming systems (PPS). However, little work has been done to evaluate their usability, or to develop criteria for such evaluations. As a result, the usability of a typical PPS is based on how easily a small set of trivially parallel algorithms can be implemented by its authors.

This paper discusses the design and results of an experiment to objectively compare the usability of two PPSs. Half of the students in a graduate parallel and distributed computing course solved a problem using the Enterprise PPS while the other half used a PVM-like library of message-passing routines. The objective was to measure usability. This experiment provided valuable feedback as to what features of PPSs are useful and the benefits they provide during the development of parallel programs. Although many usability experiments have been conducted for sequential programming languages and environments, they are rare in the parallel programming domain. Such experiments are necessary to help narrow the gap between what parallel programmers want, and what current PPSs provide.

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[1] A summary of this work appeared as: D. Szafron and J. Schaeffer, "Experimentally Assessing the Usability of Parallel Programming Systems", IFIP WG10.3 Working Conference on Programming Environments for Massively Parallel Distributed Systems, Monte Verità, Ascona, Switzerland, pp. 19.1-19.7, 1994.

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1. INTRODUCTION

In the past decade, the technology of parallel and distributed computing (henceforth simply "parallel computing") has moved from the laboratory to the commercial domain. A large infusion of research and development money has accompanied this transition and has accelerated the development of a diverse collection of innovative architectures such as hypercubes, massively parallel processor arrays, multicomputers and shared memory multiprocessors. Although each architecture achieves high performance for some classes of applications it does poorly for others, adding an extra dimension of complexity to selecting an architecture.

Unfortunately the development of software for these new hardware architectures has lagged behind. Parallel software developers must contend with problems not encountered during sequential programming. Non-determinism, communication, synchronization, fault-tolerance, heterogeneity, shared and/or distributed memory, deadlock and race conditions present new challenges. Further, if the parallelism in an application is not suited to the topology of a given parallel architecture, the designer may have to contort the program to match the machine. Underlying all of this is the implicit need for high performance.

A number of software systems have been developed to simplify the task of developing parallel software. Each is suitable for one or more architectures ranging from tightly-coupled shared-memory multiprocessors to loosely-coupled networks of workstations with distributed memory. At one extreme, some of these systems support specialized programming models that allow programmers to quickly achieve high performance for selected applications. Unfortunately, this high performance cannot be attained across all classes of applications. Other systems provide a set of low-level primitives that allow the programmer to achieve high performance for many applications, but at the expense of drastically increased software development time. In this paper we use the term parallel programming system (PPS) to encompass all software systems that support the design, implementation and execution of concurrent program components.

There are many considerations that affect the assessment of PPSs, but the majority fall into three categories [1]:

1) Performance: For the applications of interest, what kind of run-time performance will be achieved? In many organizations, performance is often considered to be a

feature of hardware alone, without proper consideration of PPSs and the performance they are (in)capable of achieving.

2) Applicability: What types of parallelism are easily expressed using the PPS? Is the PPS available on a variety of hardware platforms, and will it achieve high performance on each? Although a PPS might be available on a variety of machines, it may only achieve high performance on a specific platform.

3) Usability: How easy is application design, development, coding, testing and debugging? Some PPSs address only one of these activities, without providing support for the rest of the software development cycle.

Within each of these categories, several issues must be considered. Table 1 lists some of the most important ones.

CATEGORY	ASSESSMENT METRIC
Performance	benchmark results speed of code generated memory usage turnaround time
Applicability	portability hardware dependence programming languages supported types of parallelism supported
Usability	learning curve probability of programming errors functionality integration with other systems deterministic performance compatibility with existing software suitability for large-scale software engineering power in the hands of an expert ability to do incremental tuning

Table 1: Assessment factors.

Recently, the parallel/distributed computing community has focused its attention on the development of benchmark test suites, consisting of a diverse collection of programs, as a way of quantifying performance. Given the diversity of algorithmic techniques and communication patterns in these test suites, it is difficult for any system to provide uniformly high performance across all tests. Usually, a system does very well on a handful of test programs and has poor or mediocre performance on the rest. Since the performance issue is addressed in many other papers, we do not elaborate on it further.

There are a number of ways to assess the applicability of a programming system. Portability is an important issue in the sequential world, but has an extra dimension of complexity in the parallel world. Any programming system can be ported to a variety of hardware platforms. However, its performance may be low if its special hardware needs are not met. Availability can be assessed either globally (over a wide range of machines) or locally (meeting an individual organization's needs). Clearly, high availability of a system is meaningless if it does not support your favorite machine or base language.

Of the aspects listed here, the least frequently measured is usability. Nevertheless, it may be the most important since it directly influences the productivity of programmers. Given the extra complexity of debugging and testing parallel and distributed software, it is essential that a PPS eliminate, reduce, or at least mask the complexity. There are many papers in the literature that compare different parallel programming systems based on their technical merits (for example [2]), but none of them attempt to assess quantitatively the effect of the programming system on the productivity of the users of the system.

This paper focuses on the usability of PPSs and introduces one way to measure it. A controlled experiment was conducted in which half of the graduate students in a parallel/distributed computing class solved a problem using the Enterprise PPS [3] while the rest used a PPS consisting of a PVM-like[4] library of message passing calls called NMP [5]. The specific PPSs used in this experiment are not the focus of this paper. Instead, we argue that controlled experiments must be conducted so that PPS developers can determine which features should be included in PPSs. Although controlled experiments have been performed to compare the usability of sequential programming languages and environments [6], it is surprising that except for one [7] we know of no other comparable work for PPSs. Results of objective experiments are necessary to help narrow the gap between what parallel programmers really want and what current PPSs provide.

Section 2 describes two types of proposed experiments for measuring usability, one for novices and one for experts. The experiment described in this paper is for novices. Section 3 describes the sample problem that was used in the experiment and outlines the Enterprise and NMP solutions. Section 4 describes the design of the experiment. Section 5 presents an analysis of the experimental results. Section 6 describes how this work should influence the design of future experiments. Section 7 describes the future directions of this work.

2. MEASURING USABILITY

Quantifying and measuring usability involves human-factors considerations that are often ignored in "main-stream" computing science. Several features of a PPS determine its usability. Among these are:

1) Learning curve: How long does it take an expert or an inexperienced parallel programmer to be able to use the PPS productively? Note that some PPSs specifically address the needs of experts, while others are targeted at novices; few are suitable for both.

2) Programming errors: Some systems restrict the use of parallelism to prevent errors (e.g. Enterprise). Other systems, such as NMP and PVM, allow the user to do anything, trading flexibility for a higher chance of programming errors. Usually the potential for errors is directly related to the number of lines of user code. Therefore, systems that require more user code may be more susceptible to errors.

3) Deterministic performance: Non-determinism, common in the implementation of some algorithms and inherent in some PPSs, can significantly increase the overhead in application debugging.

4) Compatibility with existing software: Legacy software cannot be ignored. Ideally, the PPS must support the integration of existing software with minimal effort.

5) Integration with other tools: A PPS should either come with, or provide access to, a complete suite of software development tools including facilities for debugging, monitoring and performance evaluation.

Although there have been many human-factors studies of the productivity of sequential programmers [6], we know of no comparable studies for programmers developing parallel software. In [1], we proposed two experiments to assess the productivity of PPSs. The

first measures the ease with which novices can learn the PPS and produce correct, but not necessarily efficient, programs. The second measures the productivity of the system in the hands of an expert. The mechanics of these experiments are quite simple: put a group of programmers in a room, give them instructions for a PPS, give them some problems to solve, and measure what they do. For novices, we are interested in measuring how quickly they can learn the system and produce correct programs. For experts, we want to know the value of $p_{1/2}$, the time it takes to produce a correct program that achieves at least half the peak performance of the machine[3][9].

3. THE SAMPLE PROBLEM AND ITS SOLUTION

The problem chosen for the experiment was the computation of a transitive closure. This problem was used in a graduate course in parallel computing at the University of Alberta during the previous year, but all students used NMP. Although consideration was given to changing the problem (perhaps making it more challenging), we felt that a change might introduce a bias. As it turned out, although we do not regard this problem as hard, the students spent a large amount of time on it. Clearly a more challenging problem was not appropriate (with hindsight)! In future experiments, it would be better to choose a problem from a published test suite. However, the problem must be carefully selected to avoid a bias in favor of one tool over the other. The Salishan problems [2] are a good starting point, as are the Cowichan problems, a new test suite proposed by Wilson [10].

Essentially, the transitive closure program iterates until all values in a set have been assigned a value (a simplified version of [11] with an application-independent interface provided). Each iteration must traverse a graph using the information from the previous iteration to resolve additional data values. This problem has an obvious solution where each processor is responsible for a sub-graph, and the processes synchronize at the end of each iteration. It is possible to create a chaotic solution, where the processes do not synchronize, but this requires careful consideration of the termination conditions.

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[3] $p_{1/2}$ is an analogy to Hockney's $n_{1/2}$, which is the vector length on which a pipeline delivers half its peak performance. This term was found by Greg Wilson in an Internet posting.

Two data sets were provided for the students. Data set 1 contained a problem with 100,000 nodes in the graph; data set two had 1,000,000 nodes. The first data set was used as a "simpler" problem to verify program correctness; the second was more compute-intensive and was used for timings. However, the second data set also had different execution properties so that a program tuned to perform well on data set 1 would not do well on data set 2 and visa-versa.

3.1 The Enterprise Solution

In Enterprise, the interactions of processes in a parallel computation are described using an analogy based on the parallelism in a business organization [8]. Since business enterprises coordinate many asynchronous individuals and groups, the analogy is beneficial to understanding and reducing the complexity of parallel programs. Inconsistent parallel terminology (such as master-slave, pipelines or divide-and-conquer) is replaced with more familiar business terms (*assets* called *lines, departments, receptionists, individuals, divisions,* and *representatives*). Every sequential procedure that will execute concurrently is assigned an asset type that determines its parallel behavior. The user code for each of these procedures is sequential C, but a procedure call to such an asset is automatically translated into a message by Enterprise.

Consider the following user C code, assuming that `func` is an asset in the program:

```
result = func( x, y );
/* other C code */
a = result;
```

When Enterprise translates this code to run on a network of workstations, the parameters `x` and `y` are packed into a message and sent to the process that executes the asset `func`. The caller continues executing and only blocks and waits for the function result when it accesses the result `(a = result)`. A pending result that allows concurrent actions has been called a *future* [12].

Enterprise has three components: an object-oriented graphical interface, a pre-compiler, and a run-time executive. The user specifies the application parallelism by drawing a hierarchical enterprise that consists of assets. At run-time, each asset corresponds to one or more processes. Sequential procedure calls in C are translated by the pre-compiler into message send/receives across a network. The execution of the program (process/processor assignment, establishing communication links, monitoring network load) is done by the run-time executive.

In Enterprise, the transitive closure problem can be modeled as a line (pipeline) of two assets as shown in Figure 1. The double line rectangle represents the whole program (enterprise). The dashed-line rectangle represents the line asset and each inner icon represents a component. The first asset, called TC, is essentially a master process that divides the work into disjoint subsets of nodes to evaluate. The second asset, called Iterate, computes new values for each node in the subset it is assigned. Instead of having one Iterate process that sequentially traverses all the nodes in the graph, the asset is replicated eight times (as shown in Figure 1). At run-time, each of the eight replicas can traverse its subset of the problem concurrently using a separate process.

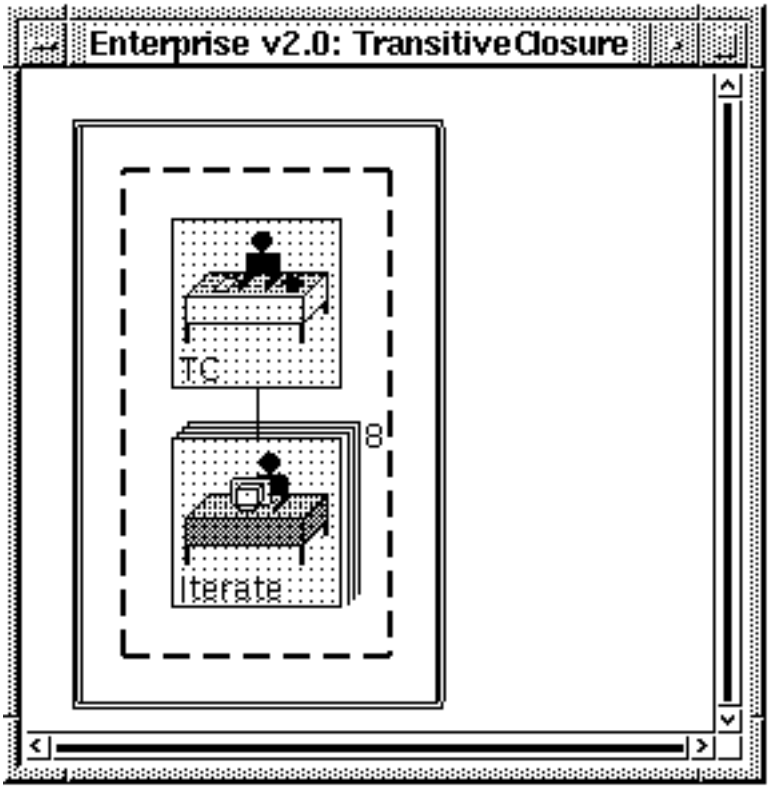


Figure 1: The Transitive Closure program in the Enterprise PPS.

When a user compiles a program, the Enterprise pre-compiler automatically inserts code to handle the distributed computation. When a user executes a program, the Enterprise run-time executive allocates the necessary number of processors to start the program, initiates processes on the processors, and dynamically allocates work to processes, ensuring that the work is evenly distributed.

3.2 The NMP Solution

The Network Multiprocessor Package (NMP) is a PVM-like message passing library built on top of sockets. Essentially it is a friendly interface to TCP and UDP. NMP provides the same basic facilities as PVM, except support for using heterogeneous processors and dynamic reconfiguration of processes is not provided.

Process/processor mappings are defined by a configuration file supplied by the user at run-time. Figure 2 shows a sample configuration file for the transitive closure problem. The user must explicitly map the processes to processors and indicate all communication paths. Processes are given ids, starting with zero for the first process in the configuration file, and sequentially thereafter. Connections are specified by a Boolean connection matrix where each entry specifies whether a process can talk to another process or not. The user must make this available to the application prior to running it, and must modify it as run-time conditions change (such as the number and/or identity of available processors). In contrast, the Enterprise asset diagram need not change as run-time conditions vary.

```
# Processors, their executable, and in/out/err files
assn110; 0;
assn111; 0; Parallel/TC/a.out -slave ; ; out1; err1
assn112; 0; Parallel/TC/a.out -slave ; ; out2; err2
assn113; 0; Parallel/TC/a.out -slave ; ; out3; err3
assn114; 0; Parallel/TC/a.out -slave ; ; out4; err4
# Process connections:
# 1 indicates connection, 0 no connection.
0 1 1 1 1
1 0 0 0 0
1 0 0 0 0
1 0 0 0 0
1 0 0 0 0
```

Figure 2. An NMP configuration file.

NMP provides a number of routines, of which the four most important are:

```
NodeInit(root_or_slave,config_file);
SendNode(who,message_ptr,send_bytes);
bytes_received=ReceiveNode(who,message_ptr,rcv_bytes);
who_array=PollAll(block_or_not);
```

Each process calls `NodeInit` to initialize its connections, `SendNode` and `ReceiveNode` to communicate, and `PollNode` to query whether there are any communications waiting. There are a variety of other support routines.

Before the experiment began, consideration was given to whether PVM should be used in the experiment, instead of the locally developed NMP. The advantage of PVM is that it is widely known. However, NMP was chosen for several reasons:

1) NMP is a subset of PVM, and has less than 20 different library calls to learn (most of which were not relevant for this experiment).

2) The documentation for NMP is less than 20 pages, simplifying the student's startup overhead.

3) NMP has been used in a graduate course for the past 5 years, with no known bugs. On the other hand, PVM is still under development and we have occasionally encountered bugs.

4. EXPERIMENTAL DESIGN

There are a number of considerations that must be taken into account in the design of a fair experiment to measure usability.

4.1 Prelude

In the preliminary planning stages of the experiment, we consulted a cognitive psychologist with expertise in designing experiments that involve human subjects. She provided us with important advice on how to conduct the experiment to avoid introducing biases. In particular, it was important that the students not know the exact nature of what was being measured in the experiment. This point had several important implications to the design of the experiment. In this case, the students were only told that they would provide us with a subjective evaluation of the tool they were using and were not told that any measurements were being taken.

4.2 Subjects

The students in the CMPUT 507 Parallel Programming graduate course at the University of Alberta were used as subjects. None of them had any previous parallel programming experience prior to taking this course. Before the experiment, the students completed assignments to program a SIMD machine (with a vectorizing Fortran compiler) and to program a distributed memory multiprocessor (with C/Fortran language extensions for doing loops in parallel - Myrias Parallel C/Fortran [13]).

In general, selecting subjects for an experiment can be a difficult task [8]. The experimenter would like the subjects chosen to be 1) *representative* so that the results from a small sample can be used to make a statement about a larger population and 2) relatively *uniform* in their abilities and experience. However, these characteristics become contradictory as the parent population becomes more heterogeneous. Using students in a graduate course and controlling their introduction to parallel computing helps reduce some of the concerns about uniformity. However, as evidenced by the results presented in Section 5, there was a wide range in the programming abilities of the students. This is not surprising since differences in the abilities of students in a programming course have been reported before (see, for example [14]). The advantage of a larger population size is that these differences tend to distort the results less. Unfortunately, although we would have liked to have more students in the experiment, the enrollment in the course dictated our sample size.

4.3 Partitioning

The class of 15 students was divided into 2 groups, one using NMP and the other using Enterprise. The assignment of students to groups was done randomly, with 7 students in the Enterprise group and 8 in the NMP group.

4.4 Instruction

The entire class was given one fifty minute lecture about NMP and one fifty minute lecture about Enterprise and were provided with documentation for both systems before they were assigned to the test groups. Each lecture described how the programming model could be used to define processes, process inter-connections and inter-process communication.

A lab demonstration of each PPS was also presented. A simple program was demonstrated that computes the squares and cubes of numbers in parallel. Although this problem is trivial and does not have the granularity to justify a parallel implementation, its simplicity allowed the students to concentrate on parallel programming issues, rather than the sequential algorithm. Each system was demonstrated for 20 minutes. Each demonstration illustrated how to convert the sequential program into a parallel one. The Enterprise and NMP solutions were then made available to the students for reference.

4.5 Student Help

In addition to the instructor, a teaching assistant who was familiar with both NMP and Enterprise was available to answer student questions. All queries for help were logged with the name of the student, the date and the nature of the question asked. Students were encouraged to discuss the assignment with each other, but they were expected to do the assignment individually.

4.6 Environment

Students had access to 50 Sun 4 workstations that were shared with several hundred undergraduates. Students were not allowed to use the machines during prime-time and were restricted to a single processor for program development and testing, and a maximum of 8 machines for timing runs. During the final three days before the assignment was due, the students were given dedicated access to the machines from midnight to 8 am so that they could obtain accurate timings of their executions.

Each student account contained a modified *zsh* shell (*zsh* is a public domain shell which is compatible with the Bourne shell but has C-shell job control enhancements). The shell was modified to log all commands executed by the students (date, time, command, and exit status of the command). Enterprise was also instrumented to record all editing, compiling and execution actions. The students were not told about the instrumentation. This is an important point since subjects who know about instrumentation may consciously or subconsciously modify their behavior. For example, a subject may try to avoid multiple compilations if it is known that compiles are being counted. On the other hand, it is necessary to conduct these experiments in an ethical manner so that the privacy of the subjects is not violated. The instrumentation only counted statistics directly connected to the PPS as opposed to monitoring the contents of private files such as mail files. That is, we only gathered statistics similar to those obtained by the Unix *lastcomm* utility.

4.7 Time Frame

Students were given two weeks to complete the assignment.

4.8 Epilogue

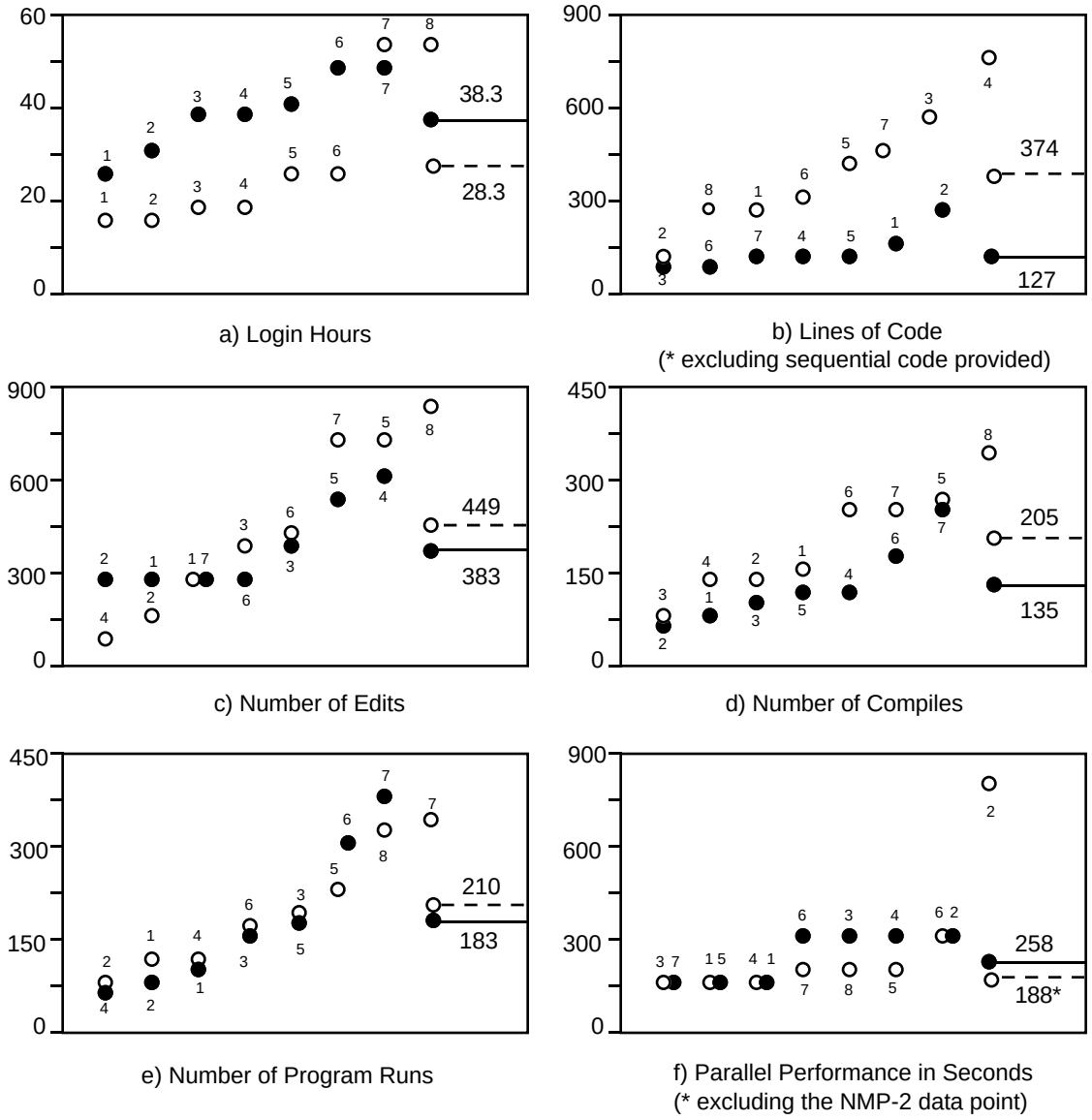
At the experiment's conclusion, students were asked to submit a two-page write-up commenting on their respective PPS, and were encouraged to be blunt about what they liked and disliked.

5. EXPERIMENT RESULTS

Prior to the experiment, we tried to anticipate events that might influence the results. For example, it was known that the NMP documentation was superior to that for Enterprise. Also, since Enterprise was an evolving system, it was inevitable that students would find bugs. The question was: how much would these factors bias the results? Intuitively, one would expect that since Enterprise is a higher-level tool, the Enterprise students would write less code and develop a working program more quickly than the NMP students. However, since NMP is a low-level tool, the NMP students would have more implementation alternatives. Finally, Enterprise has certain run-time overheads (such as larger message sizes, hidden manager processes and additional messages). These points suggested that NMP should have better run-time performance.

How does one objectively measure usability? Intuitively, one PPS is more usable than another if it is easier to solve a problem. Our experiment measured five factors that seem to be indirect measures of usability as well as one factor (run-time performance) that may be traded off against increased usability. Figure 3 shows the six statistics that were analyzed. In the first five cases, a lower number should indicate higher usability, while in the sixth case, a lower number indicates better run-time performance.

1. The number of hours each student was logged in, actively working on the assignment (idle periods of more than 15 minutes are not included).
2. The number of lines of code in the solution program (including blank lines and comments). Students were given the sequential program (128 lines of code) and were expected to parallelize it. They were also given a library containing the parts of the program that did not have to be altered (over 1000 lines of code). The figure shows the parallel code written less the 128 lines of sequential code.
3. The number of editing sessions.
4. The number of compiles that attempted to link the program together (i.e., compiles which failed because of syntax errors were not included).
5. The number of times the students tested their parallel program by running it.
6. The execution times of their program on data set 2.



Hollow circles are NMP data points and solid circles are Enterprise data points. In graphs a) to e), smaller numbers indicate better usability. In graph f) smaller numbers indicate better performance. Solid lines represent averages of Enterprise data points. Dashed lines represent averages of NMP data points.

Figure 3. Experiment results.

In each figure, the hollow circles represent NMP data points (8 students) and the solid circles represent Enterprise data points (7 students). Each student is given a number, so the reader can compare an individual's performance across graphs. These graphs are ordered with the best performer on the left and the worst on the right. For example, Figure 3a) shows that Enterprise student 2 spent the second least amount of time working on the assignment, but Figure 3b) shows that this student generated the largest program of any of

the Enterprise students. Finally, the right-hand side of each graph shows the average of the NMP students (dashed line) and the Enterprise students (solid line).

The statistics support our initial expectations that students would do less work (higher usability) with Enterprise, but get better run-time performance with NMP. Enterprise students did 14% fewer edits, wrote 66% fewer lines of code, did 34% fewer compiles and 13% fewer program test runs. However, perhaps surprisingly, they used 26% more login time. Why does this apparent anomaly exist? There are several reasons:

1) Enterprise compiles take roughly 4 times as long as the regular C compiles used by the NMP students. Enterprise must preprocess the user's code by making several passes over the input file before it produces a file that is compiled by the C compiler. From Figures 3a) and 3c), the average NMP user compiled 7.2 times per hour, while the average Enterprise user compiled only 3.5 times per hour.

2) Enterprise includes an option to replay a computation using animation, so that the user can see (and inspect) the messages being sent and see the status of each process [15]. If the user watches an animation of the transitive closure program to completion using the default settings, it could take as long as 10 minutes. Each Enterprise user, on average, used this feature 25 times.

3) The students uncovered nine bugs in Enterprise; two of them serious errors that affected the student's progress. Although turnaround on bug fixes was rapid (less than 24 hours), most students assumed that the bug was in their program and not in Enterprise. We do not know how much time they devoted to solving these problems before they reported them.

4) Since the NMP performance was better, Enterprise students spent more time doing performance tuning to try to obtain better speed-ups.

Never having done an experiment like this before, we were quite unprepared for the variation and magnitude of the numbers. For example, the average NMP student performed 205 compiles (excluding compiles with syntax errors). To us, this was an astonishingly large number. We are not sure how to interpret this: was the assignment too difficult, is it a comment on our student's programming ability, or is it a comment on their difficulty in learning distributed computing?

Enterprise solutions required considerably fewer lines of code to be written than did their NMP counterparts. Superficially, this appears to be a strong endorsement for a

higher-level programming tool. However, this conclusion must be qualified. The implication is that fewer lines of code implies fewer errors. However, it is possible that properly-designed and clearly-written code may take more lines, contain fewer errors, take less time to write and debug, and run more efficiently. An instance of this can be seen in Figure 3, where the smallest NMP program (254 lines of code) had the worst run-time performance, but the largest (911 lines) was one of the fastest! The strength of a high-level programming tool, such as Enterprise, is not that the user writes fewer lines of code. Rather, it is that the time saved during coding can be used in the design of a parallel solution, without being distracted by unnecessary details.

We used lines of code in a program as a simple measurement of effort expended by the programmers, as is done in most industrial settings. More complex measurements could have been used like Halstead's effort equation [16] or one of many other metrics [17]. However, automating these metrics will require some additional parsing support. We are considering this change for the next experiment.

As expected the NMP solutions (excluding the anomalous NMP-2 data point) had better run-time performance (27%). For this problem, the Enterprise communication time could be as high as 30% of the execution time depending on how the problem was solved. Since Enterprise managers forward messages to replicated assets there could be twice as many messages as in a hand-coded NMP solution, where the master process communicates directly with its slaves. In addition, at least two of the Enterprise solutions had bugs in them whereby two futures overlapped, forcing sequential execution where concurrent execution was intended.

Enterprise claims that it lets users avoid common parallel programming mistakes such as deadlock, synchronization errors and failure to consume all messages. From the user feedback, it appears this claim is partially justified: one NMP student had problems with deadlock while two had problems coordinating messages. However, the Enterprise model introduced different parallel programming mistakes that the students might stumble on, such as the overlapping futures problem mentioned above. Superficially, it appears that Enterprise has traded one problem for another. However, it is important to note that the Enterprise problems only affected the *efficiency* of the code, while the NMP problems affected the *correctness* of the code.

Why are the numbers in Figure 3 so large? This assignment was a learning experience for the students, and as such they did a lot of experimenting. For example, log files show

that some students did not parameterize their code for the number of processors used; they compiled separate versions for 1, 2, 3, ... 8 processors, increasing the number of edits and compiles. There was also a lot of experimenting with granularity. The programming problem intentionally had the property that the performance parameters that the user might tune for best results on data set 1 did not give good performance for data set 2.

All the results presented must be qualified by the sample size used for this experiment. Fifteen students is not enough to ensure the statistical validity of any claims made based on these numbers. Unfortunately, although we would have liked to have more students in the experiment, this is the typical size of our graduate courses. It is not likely that any future experiments will have a larger sample size.

During the experiment, the students asked many questions and made many comments that highlighted the conceptual difficulty of several key concepts in parallel computing. The most important new non-sequential concepts are process startup, process termination and passing pointers between processes. What special operations like variable initializations need to be done when a process (or asset) is called the first time, versus when the process is called subsequently? How are termination conditions checked and how should the processes (assets) exit gracefully? Since distributed programs have separate address spaces on different processes, how should the source code be changed to pass pointer data structures between processes? These concepts are important and should be specifically highlighted in the documentation for all PPSs.

6. A NEW EXPERIMENT

The experiment revealed two important deficiencies in the experimental design itself, both of which are easily corrected. First, since usability involves the time it takes to obtain a solution with a certain performance, the experiment must define performance milestones and all measurements must be grouped based on these milestones. For example, statistics should be reported separately on the time taken to learn the tool, the time taken to obtain a working solution and the time spent tuning for performance. In fact, we attempted to do this in the experiment but half of the students ignored the milestones. The instrumentation must be changed to ensure these statistics are gathered.

Second, the experiment was conducted using inadequate hardware resources. The amount of main memory available made the graphical user interface too slow. In addition, the workstations were shared with undergraduates so it was difficult to take accurate

performance readings except at night. In general, hardware resources should be provided that adequately meet the requirements of all PPSs being evaluated so that no biases are introduced.

Ideally, a future experiment would be enlarged to include a larger student population, more than one programming problem and more PPSs (an experiment under consideration involves comparing PVM, Enterprise, Linda [18] and Orca [19]). As well, it would be interesting to do these experiments using both novice and expert parallel programmers. It is not obvious which of the results obtained using novice parallel programmers carry over to experienced parallel programmers.

One interesting extension to the experiment that will improve the significance of the experimental results, would be to establish some control data points. In CMPUT 507, students did two parallel programming assignments (vector processing and Myrias) before the experiment. Data gathered from these two assignments would allow us to better understand the student's learning curve, and help us put each student's result in the proper perspective. It might provide some insight into learning effects, particularly if the experiment were redesigned so that we changed the order in which students were taught the PPSs. For example, for historical reasons, vector processing has always been taught first in CMPUT 507. Would the student's learning curve be different if they were taught PVM first?

Finally, having done one experiment, it may be difficult to conduct future experiments that are unbiased. We have acquired a "reputation" among the graduate students in our department. Since the student body in general now knows about the experiment and the factors that were measured, this may consciously or subconsciously bias participants in future experiments. For example, although we did not associate names with any of our data points, some students felt uncomfortable (and even embarrassed) when they were told of the experiment results. Perhaps these students were able to identify which data point were theirs knowing, for example, that they performed a lot of compiles. We suspect that future students taking this course will be conscious about the number of compiles and program executions they attempt.

7. CONCLUSIONS

This paper has identified an area where the parallel/distributed computing community has been negligent in providing quantitative data. Hardware vendors are quick to cite

measurements that flatter the performance of their machines (MIPS, SPECmarks, Whetstones, etc.), but neglect to quantify the usability of their software. The growing base of parallel computing users could significantly benefit from an objective assessment of the usability of PPSs.

This experiment had four results:

1. **It demonstrated that the usability of PPSs can be measured objectively**.
2. **It supported the claim that Enterprise is more usable than a low-level message passing library**. Further, since Enterprise is still under development and the bugs that may have affected the results in this experiment have been fixed, one can expect a subsequent experiment to reveal a more decisive advantage for the high-level tool.
3. **It identified some fundamental PPS independent key concepts that are difficult for most novice parallel programmers to understand**. These concepts should be stressed in the documentation for all PPSs.
4 **It produced several direct benefits to the Enterprise PPS**. This issue is important for any designer of a PPS. User feedback helps identify potential problem areas in the programming model, user interface and run-time performance. For Enterprise, a number of major problems were identified. We must consider the possibility of adding a textual interface since many students wanted to work at home and did not have an X-windows interface. The statistics indicate that the speed of the Enterprise pre-compiler must be improved. Student comments caused us to increase our priority on debugging tools. Program solutions revealed some subtle flaws/omissions in the programming model. Finally, the students identified major weaknesses in the Enterprise documentation. Except for the documentation, we were not aware of any of the other problems. We have used this information to alter some of our implementation directions.

The Enterprise PPS is based on using sequential code with parallel annotations that are expressed graphically. This approach is not an all-encompassing general-purpose solution for all parallel applications, but allows an important class of problems to be solved more quickly. We believe these high-level approaches to parallel computing will become more prevalent as their obvious software engineering advantages become recognized. It is easy to make comparisons on paper, emphasizing our perception that Enterprise has a high

degree of usability. However, until scientific experiments are done to compare PPSs, anyone's claim is as valid as any other.

Although this is only a first attempt at measuring the usability of PPSs, the experiment nevertheless highlights the human factors issues that have been neglected to date. We propose that the above experiment (or variations on it) should be an integral part of the development cycle for parallel software tools. Given the diversity of programming systems available, researchers need more feedback as to what works well and why. We recognize that the cost of performing such quantitative measurements will be large. However, the cost of not performing them, as borne by a group which selects a low-usability PPS, will certainly be much larger.

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