PRO: A Model for the Design and Analysis of Efficient and Scalable Parallel Algorithms

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Abstract

We present a new parallel computation model called the Parallel Resource-Optimal computation model. PRO is a framework being proposed to enable the design of efficient and scalable parallel algorithms in a manner that is architecture independent and to simplify the analysis of such algorithms. Three key features distinguish PRO from existing parallel computation models. First, the design and analysis of a parallel algorithm in the PRO model is performed relative to the time and space complexity of a specific sequential algorithm. Second, a PRO algorithm is required to be both time- and space-optimal relative to the reference sequential algorithm. Third, the quality of a PRO algorithm is measured by the maximum number of processors that can be employed while optimality is maintained. Inspired by the Bulk Synchronous Parallel model, an algorithm in the PRO model is organized as a sequence of *supersteps* each of which consists of distinct computation and communication phases. The supersteps are however not required to be separated by synchronization barriers. Both computation and communication costs are accounted for in the runtime analysis of a PRO algorithm. Experimental results on parallel algorithms designed using the PRO model—and implemented using its accompanying programming environment SSCRAP—demonstrate that the model indeed delivers efficient and scalable implementations on a wide range of platforms.

Key words: Parallel computers, Parallel computation models, Parallel algorithms, Complexity analysis

I. Introduction

As Akl in a book on parallel computation points out, a model of computation should ideally serve two major purposes [3]. First, it should describe a computer. In this role, a model should attempt to capture the essential features of an existing or contemplated machine while ignoring less important details of its implementation. Second, it should serve as a tool for analyzing problems and expressing algorithms. In this sense, a model needs not necessarily be linked to a real computer but rather to an understanding of computation.

In the realm of sequential computation, the Random Access Machine (RAM) has been a standard model for many years, successfully achieving both of these purposes. It has served as an effective model for hardware designers, algorithm developers, and programmers alike. Only recently has the focus on external memory and cache issues uncovered a need for more refined models. When it comes to parallel computation, there has not been an analogous, universally accepted model that has been as successful. This is in part due to the complex set of issues inherent in parallel computation.

The performance of a sequential algorithm is adequately evaluated using its execution time, one of the reasons that made the RAM powerful enough for algorithm analysis and design. On the other hand, the performance evaluation of a parallel algorithm involves several metrics. Perhaps the most important metrics are *speedup*, *optimality* (or *efficiency*), and *scalability*. To enjoy similar success as that of the RAM, a parallel computation model should incorporate at least these metrics and be simple to use at the same time. In order to simplify the design and analysis of *resource-optimal*, *scalable*, and *portable* parallel algorithms, we propose the Parallel Resource-Optimal (PRO) computation model. The PRO model was first introduced in a short conference paper [1]. Here we describe the model in detail and provide experimental results to demonstrate its practical relevance.

The PRO model is inspired by the Bulk Synchronous Parallel (BSP) [4] and the Coarse Grained Multicomputer (CGM) [5] models. In the BSP model a parallel algorithm is organized as a sequence of *supersteps* with distinct computation and communication phases. The emergence of the BSP model marked an important milestone in parallel computation. The model introduced a desirable structure to parallel programming, and was accompanied by the definition and implementation of communication infrastructure libraries [6, 7, 8]. Recently, a textbook on scientific parallel computation using the BSP model has appeared [9]. From an algorithmic (as opposed to a programming) point of view, we believe that the relatively many and machine-specific parameters involved in the BSP model make the design and analysis of algorithms somewhat cumbersome. The CGM model partially addresses this limitation as it involves only two parameters, the input size and the number of processors. The CGM model is a specialization of the BSP model in that the communication phase of a superstep is required to consist of single long messages rather than multiple short ones. A drawback of the CGM model is the lack of an *accurate* performance measure; the number of communication rounds (supersteps) is usually used as a quality measure, but as we shall see later in this paper, this measure is sometimes inaccurate.

The PRO model inherits the advantages offered by the BSP and the CGM models. It also reflects a compromise between further theoretical and practical considerations in the design of optimal and scalable parallel algorithms. Three key features distinguish the PRO model from existing parallel computation models. These are: *relativity*, *resource-optimality*, and a new quality measure referred to as *granularity*.

Relativity pertains to the fact that the design and analysis of a parallel algorithm in PRO is done relative to the time and space complexity of a *specific* sequential algorithm. As a consequence, the parameters involved in the analysis of a PRO-algorithm are: the number of processors p, the input size n, and the time and space complexity of the reference sequential algorithm $\mathcal{A}$. Note that speedup and optimality are metrics that are relative in nature as they are expressed with respect to some sequential algorithm, and this forms the major reason for our focus on relativity. The notion of relativity is also relevant from a practical point of view, since a parallel algorithm is usually designed not from scratch, but rather starting from a sequential algorithm.

A PRO-algorithm is required to be both time- and space-optimal, hence resource-optimal, with respect to the reference sequential algorithm. A parallel algorithm is said to be time- (or work-) optimal if the overall *computation and communication* cost involved in the algorithm is proportional to the time complexity of the sequential algorithm used as a reference. Similarly, it is said to be space-optimal if the overall memory space used by the algorithm is of the same order as the memory usage of the underlying sequential version. As a consequence of its time-optimality, a PRO-algorithm always yields *linear speedup* relative to the reference sequential algorithm, *i.e.*, the ratio between the sequential and parallel runtime is a linear function of the number of processors p. The resource optimality requirement set in the PRO model enables one to concentrate only on practically useful parallel algorithms. Here optimality is required only in an asymptotic sense, which leaves enough slackness for easy design and analysis of algorithms.

Before turning to the quality measure of a PRO algorithm, we wish to underscore the consequences of the novel notion of relativity. In PRO, instead of directly comparing algorithms that solve the same problem, a two-leveled approach is taken. First, a reference sequential algorithm $\mathcal{A}$ with a particular space and time complexity is selected. Then, parallel algorithms that are resource-optimal with respect to $\mathcal{A}$ are compared. The latter comparison, *i.e.*, the quality of a PRO algorithm, is measured by the range of values the parameter p can assume while linear speedup is maintained. It is captured by an attribute of the model called the granularity function $\text{Grain}(n)$. In particular, a PRO-algorithm with granularity $\text{Grain}(n)$ is required to yield linear speedup for all values of p such that $p = O(\text{Grain}(n))$. In other words, the algorithm is required to be fully *scalable* for $p = O(\text{Grain}(n))$. The higher the function value $\text{Grain}(n)$, the better the algorithm. The final evaluation of a PRO-algorithm for a given problem must of course take into account both the time and space complexity of the reference sequential algorithm and

the granularity function. A new result will typically be presented as follows: *Problem* Π *has a PRO-algorithm with Grain*$(n) = g(n)$ *relative to a sequential algorithm* $\mathcal{A}$ *with time complexity* $T_{\mathcal{A}}(n)$ *and space complexity* $S_{\mathcal{A}}(n)$. This simply means that for every number of processors p and input size n with $p = O(g(n))$, there is a parallel algorithm in the PRO model for problem Π where the parallel runtime is $O(\mathrm{T}_{\mathcal{A}}(n)/p)$ and each processor uses $O(\mathrm{S}_{\mathcal{A}}(n)/p)$ memory.

In addition to describing—and arguing for the need for—the PRO model, a twin goal of this paper is to provide experimental evidence to help validate the model. To this end, we present results on parallel algorithms for list ranking and sorting designed using the PRO model. These algorithms were implemented using SSCRAP, a C++ communication infrastructure library for implementing BSP-like parallel algorithms; SSCRAP is developed by Essaïdi, Guérin Lassous and Gustedt [10, 11]. Our experiments were run on several platforms, including an SGI Origin 3000 parallel computer and a PC cluster. The results we obtained show that designing algorithms within the framework of the PRO model indeed offers linear speedup and a high degree of scalability across a variety of platforms.

The rest of the paper is organized as follows. In Section II we highlight the limitations of a few relevant existing parallel computation models, to help justify the need for the introduction of the new model PRO. In Section III the PRO model is presented in detail, and in Section IV it is systematically compared with a selection of existing parallel computation models. In Section V we illustrate how the PRO model is used in the design and analysis of algorithms using three examples: matrix multiplication, list ranking and sorting. The latter two algorithms are used in our experiments, the setting and the results of which are discussed in Section VI. We conclude the paper in Section VII with some remarks.

II. Existing models and their limitations

There exists a plethora of parallel computation models in the literature. Our brief discussion in this section focuses on just three of them, the Parallel Random Access Machine (PRAM), the BSP, and the CGM; we will also in passing mention a few other models. The PRAM is discussed not to reiterate its failure to capture real machine characteristics but rather to point out its limitations even as a theoretical model. The BSP and CGM models are discussed because the PRO model is derived from them. The models discussed in this section are in a loose sense divided into two groups as 'dedicated models' (to either software or hardware) and 'bridging

models' (between software and hardware).

A. Dedicated models

1) The PRAM family of models: In its standard form, the PRAM model [12, 13] consists of an arbitrarily large number of processors and a shared memory of unbounded size that is uniformly accessible to all processors. In this model, processors share a common clock and operate in lock-step, but they may execute different instructions in each cycle.

The PRAM is a model for *fine-grain* parallel computation as it supposes that the number of processors can be arbitrarily large. Usually, it is assumed that the number of processors is polynomial in the input size. However, practical parallel computation is typically *coarse-grain*. In particular, on most existing parallel machines, the number of processors is several orders of magnitude less than the input size. Moreover, the assumption that memory is uniformly accessible to all processors is in obvious disagreement with the reality of practical parallel computers.

Despite its serious limitation of being an 'idealized' model for parallel computation, the standard PRAM model still serves as a theoretical framework for investigating the maximum possible computational parallelism available in a given task. Specifically, on this model, the NC versus P-complete dichotomy [14] is used to reflect the ease/hardness of finding a parallel algorithm for a problem.

Unfortunately, the NC versus P-complete dichotomy has several limitations. First, P-completeness does not depict a full picture of non-parallelizability since the runtime requirement for an NC parallel algorithm is so stringent that the classification is confined to the case where up to polynomial number of processors in the input size is available. For example, there are P-complete problems for which less ambitious, but still satisfactory, runtime can be obtained by parallelization in PRAM [15]. In a fine-grained setting, since the number of processors p is a function of the input size n, it is customary to express speedup as a function of n. Thus the speedup obtained using an NC-algorithm is sometimes referred to as exponential. In a coarse-grained setting, speedup is expressed as a function of only p and some recent results [5, 16, 17, 18] show that this approach is practically relevant.

Second, an NC-algorithm is not necessarily work-optimal, and thus not resource-optimal, considering runtime and memory space as resources one wants to use efficiently.

Third, even if we restrict ourselves to work-optimal NC-algorithms and apply Brent's scheduling principle [19], which says an algorithm in theory can be simulated on a machine with fewer processors by only a constant factor more work, implementations of PRAM algorithms often do not reflect this optimality in practice [20]. This is mainly because the PRAM model does not account for non-local memory access (communication), and a Brent-type simulation relies heavily on cheap communication.

To overcome the defects of the PRAM related to its failure of capturing real machine characteristics, the advocates of shared memory models propose several modifications to the standard PRAM model. In particular, they enhance the standard PRAM model by taking practical machine features such as memory access, synchronization, latency and bandwidth issues into account. Pointers to the PRAM family of models can be found in [21].

2) Distributed memory models: Critics of shared memory models argue that the PRAM family of models fails to capture the nature of existing parallel computers with *distributed* memory architectures. Examples of distributed memory computational models suggested as alternatives include the Postal Model [22] and the Block Distributed Memory (BDM) model [23]. Other categories of parallel models such as low-level, hierarchical memory, and network models are briefly reviewed in [21].

These models are very close to the architecture considered and the associated algorithms are often not portable from one architecture to another.

B. Bridging models

Valiant in his seminal paper [4] underscored that a successful parallel computation model needs to act as an efficient 'bridge' between software and hardware. He introduced the BSP as a candidate bridging model and argued that it could serve as a standard model for parallel computation.

1) BSP: The BSP model consists of a collection of processor/memory modules connected by a router that can deliver messages in a point-to-point fashion. An algorithm in this model is divided into a sequence of *supersteps* separated by barrier synchronizations. A superstep has distinct computation and communication phases. In a superstep, a processor may send (and receive) at most h messages. Such a communication pattern is called an h*-relation* and the basic

task of the router is to realize arbitrary h-relations. Note that, here, h relates to the total size of communicated data during a superstep.

The BSP model uses the four parameters, n, p, L, and g. Parameter n is the problem size, p is the number of processors, L is the minimum time between successive synchronization operations, and g is the ratio of overall system computational capacity per unit time divided by the overall system communication capacity per unit time.

The introduction of the BSP model initiated several subsequent studies suggesting various modifications. For example, Culler *et al.* [24] proposed a model that extends the BSP model by allowing asynchronous execution and by better accounting for communication overhead. Their model is coined LogP, an acronym for the four parameters (besides the problem size n) involved. Models such as LogP involve many parameters making design and analysis of algorithms difficult. Analysis using the BSP model is not as difficult, but still not as simple as it could be. In fact, to simplify analysis while using the BSP model, one often neglects the latency L for problems of large enough size. Ideally, for the design of portable algorithms, it is important to abstract away specific architectural parameters. This issue is well-captured in the PRO model.

2) CGM: The CGM model [5, 16] was proposed in an effort to retain the advantages of BSP while keeping the model simple. The CGM model consists of p processors, each with $O(n/p)$ local memory, interconnected by a router that can deliver messages in a point-to-point fashion. A CGM algorithm consists of an alternating sequence of *computation rounds* and *communication rounds* separated by barrier synchronizations. A computation round is equivalent to the computation phase of a superstep in the BSP model. A communication round usually consists of a single h-relation with

$$h \approx n/p. \tag{1}$$

An important advantage of the CGM model compared to BSP is that all the information sent from one processor to another in one communication round is packed into one long message, striving to minimize communication overhead and latency. Thus, the only parameters involved in the CGM model are p and n, a fact that simplifies design and analysis of algorithms.

Assumption (1) has interesting implications on the design and analysis of algorithms. To make these implications more apparent, we first distinguish between parallel algorithms where the communication time to computation time ratio is a constant and those algorithms where the

ratio is some function of the input size.

Suppose we have a CGM algorithm where the communication time to computation time ratio is a constant. Suppose also that assumption (1) holds. Then, since each superstep has a complexity of $\Theta(h) = \Theta(n/p)$, the only parameter of the model that distinguishes one algorithm from another is the number of supersteps. This direction was followed for instance in [16] where a long list of algorithms that are designed under these assumptions is given.

However, there exists a large class of problems for which there are no known CGM algorithms with constant communication time to computation time ratio. Problems with super-linear time sequential algorithms, such as sorting and matrix multiplication, belong to this class. For such problems and their corresponding parallel algorithms, communication alone cannot be a complexity measure and hence one needs to consider computation as well.

Furthermore, even for problems whose algorithms are such that the stated ratio is constant, assumption (1) turns out to be quite restrictive. We shall illustrate this in Section V-B using the *list ranking* problem as an example. In particular, we will show that the CGM model fails to identify competitive algorithms when using the number of supersteps as a quality measure.

III. The PRO model definition

The PRO model is an algorithm *design* and *analysis tool* used to deliver a practical, optimal, and scalable parallel algorithm relative to a specific sequential algorithm whenever this is possible. Let $\mathrm{T}_{\mathcal{A}}(n)$ and $\mathrm{S}_{\mathcal{A}}(n)$ denote the time and space complexity of a specific sequential algorithm $\mathcal{A}$ for a given problem with input size n. Let $\mathrm{Grain}(n)$ be a function of n. The PRO model is defined to have the attributes given in Table I. In the following we will argue for each of these attributes turn by turn.

Attribute A states that optimality in PRO is a relative notion. Thus in PRO we could speak of an optimal parallel algorithm for a problem even if an optimal sequential algorithm for the problem is unknown. We will illustrate this point using the matrix multiplication problem as an example in Section V. An implication of attribute A is that PRO does not define a complexity class.

As discussed in the LogP paper [24], technological factors are forcing parallel systems to converge towards systems formed by a collection of essentially complete computers connected by a robust communication network. The *machine* model assumption of PRO (attribute B) is

TABLE I

ATTRIBUTES OF THE PRO MODEL

A. *Relativity:*

The time and space requirements of a PRO-algorithm for a problem (of input size n) are measured relative to the time and space requirements $\mathrm{T}_{\mathcal{A}}(n)$ and $\mathrm{S}_{\mathcal{A}}(n)$ of a specific sequential algorithm $\mathcal{A}$ that solves the same problem.

B. *Machine Model:*

The underlying machine is assumed to consist of p processors each of which has a private memory of size $M = O(\frac{\mathrm{S}_{\mathcal{A}}(n)}{p})$. The processors are assumed to be interconnected by some communication device (such as an interconnection network or a shared memory) that can deliver messages in a point-to-point fashion. A message can consist of several machine words.

C. *Coarseness Assumption:*

The size of the local memory of each processor is assumed to be big enough to store p words. That is, the relationship $p \leq M$ is assumed to hold.

D. *Execution Model:*

A PRO algorithm is organized as a sequence of *supersteps,* each consisting of a local computation phase and an interprocessor communication phase. In particular, in each superstep, each processor

D.1. sends at most one message to every other processor,

D.2. sends and receives at most M words in total, and

D.3. performs local computation.

E. *Runtime Analysis:*

Both *computation* and *communication* are accounted for in the runtime analysis of a PRO algorithm. In particular,

E.1. a processor is charged a unit of time per operation performed locally, and

E.2. a processor is charged a unit of time per machine word sent or received.

F. *Optimality Requirement:*

For every value $p = O(\mathrm{Grain}(n))$, a PRO algorithm is required to have

F.1. a number of supersteps $\mathrm{Steps}(n,p) = O(\frac{\mathrm{T}_{\mathcal{A}}(n)}{p^2})$, and

F.2. a parallel runtime $\mathrm{T}(n,p) = O(\frac{\mathrm{T}_{\mathcal{A}}(n)}{p})$.

G. *Quality Measure:*

The *granularity* function $\mathrm{Grain}(n)$ measures the *quality* of the algorithm.

consistent with this convergence and maps well on several existing parallel computer architectures. The memory requirement $M = O(\frac{\mathrm{S}_{\mathcal{A}}(n)}{p})$ ensures that the space utilized by the underlying sequential algorithm is uniformly distributed among the p processors. Since we may, without loss of generality, assume that $\mathrm{S}_{\mathcal{A}}(n) = \Omega(n)$, the implication is that the private memory of each processor is large enough to store its 'share' of the input and any additional space the sequential algorithm might require. When $\mathrm{S}_{\mathcal{A}}(n) = \Theta(n)$, note that the input data must be uniformly

distributed on the p processors. In this case the machine model assumption of PRO is similar to the assumption in the CGM model [5].

The *coarseness* assumption $p \leq M$ (attribute C) is consistent with the structure of existing parallel machines and those to be built in the foreseeable future. The assumption is required to simplify the implementation of gathering messages on or broadcasting messages from a single processor.

In terms of *execution* (attribute D) a PRO-algorithm consists of a sequence of *supersteps* (or rounds). A superstep has distinct local computation and inter-processor communication phases. The *length* of a superstep on each processor is determined by the sum of the time used for communication and the time used for local computation (see attributes E1 and E2). The length of a superstep in the parallel algorithm seen as a whole is the maximum over the lengths of the superstep on all processors. We can conceptually think as if the supersteps are synchronized by a barrier set at the end of the longest superstep across the processors. However, in PRO the processors are not in reality required to synchronize at the end of each superstep. The parallel runtime $\mathrm{T}(n,p)$ of the algorithm is the sum of the lengths of all the supersteps. Notice that the hypothetical barriers introduce only a multiplicative factor of 2 compared with an analysis that does not assume the barriers.

In PRO, since a processor sends at most one message to every other processor in each superstep (attribute D1), each processor is involved in at most $2(p-1)$ messages per superstep. Hence the total amount of messages that a PRO-algorithm will be involved with is $2(p-1)\mathrm{Steps}(n,p)$ and the overall contribution of the latency L (as in an BSP analysis) is at most $2L(p-1)\mathrm{Steps}(n,p)$. Therefore, the requirement that the number of supersteps be bounded by $O(\frac{\mathrm{T}_{\mathcal{A}}(n)}{p^2})$ (attribute F1) implies that the overall time paid per processor for *latency* is $O(\mathrm{T}_{\mathcal{A}}(n)/p)$ and hence within the some bound as the parallel runtime $O(\mathrm{T}_{\mathcal{A}}(n)/p)$ we would like to achieve. Observe that in the extreme case where

$$\mathrm{Steps}(n,p) = \Theta(\frac{\mathrm{T}_{\mathcal{A}}(n)}{p^2}) \tag{2}$$

latency could be the practically dominant term in the overall parallel runtime expression. Since latency is a parameter primarily determined by physical restrictions (such as the speed of light), and hence unlikely to improve as other architectural features, an algorithm with such a number of supersteps may no longer be portable across architectures.

On the other hand, the bandwidth of an architecture is not subject to such physical restrictions. In fact computation and communication contribute to the overall runtime in similar terms as far as bandwidth is concerned. To account for bandwidth restrictions of an architecture, in PRO, each processor is charged a unit of time per word sent and received (attribute E2). This is not an unrealistic assumption noting that the network throughput (accounted for in machine words) on modern architectures such as high performance clusters is relatively close to the CPU frequency and to the CPU/memory bandwidth.

These properties imply that the BSP complexity of any PRO algorithm can be estimated by

$$g \cdot O(\mathrm{T}(n,p)) + L \cdot O(\mathrm{Steps}(n,p)). \tag{3}$$

The condition $\mathrm{T}(n,p) = O(\frac{\mathrm{T}_{\mathcal{A}}(n)}{p})$ (attribute F2) *requires* that a PRO-algorithm be optimal, i.e., yield linear speedup, relative to the sequential algorithm used as a reference. This requirement ensures the potential practical use of the parallel algorithm. Besides the extreme case (2), the first term dominates in the BSP analysis (3) and in general latency considerations may be neglected for PRO-algorithms.

The function $\mathrm{Grain}(n)$ is a *quality measure* for a PRO algorithm (attribute G). In particular, for every number of processors p such that $p = O(\mathrm{Grain}(n))$, a PRO algorithm gives a linear speedup with respect to the reference sequential algorithm. The objective in designing a PRO algorithm is to make $\mathrm{Grain}(n)$ as high as possible, thereby increasing its scalability. As the following observation shows, there is an upper bound on $\mathrm{Grain}(n)$ set by the complexity of the reference sequential algorithm.

Observation 1: A PRO algorithm relative to a sequential algorithm $\mathcal{A}$ with time complexity $\mathrm{T}_{\mathcal{A}}(n)$ and space complexity $\mathrm{S}_{\mathcal{A}}(n)$ has maximum granularity

$$\mathrm{Grain}(n) = O\left(\sqrt{\mathrm{S}_{\mathcal{A}}(n)}\right).$$

A PRO algorithm that achieves this is said to have *optimal grain*.

Proof: One arrives at this result from two different sets of PRO-attributes. The bound $M = O(\frac{\mathrm{S}_{\mathcal{A}}(n)}{p})$ on the size of the private memory of each processor (attribute B) and the coarseness assumption $p \leq M$ (attribute C) taken together imply the bound $p = O(\sqrt{\mathrm{S}_{\mathcal{A}}(n)})$. Further, the requirement $\mathrm{Steps} = O(\mathrm{T}_{\mathcal{A}}(n)/p^2)$ on the number of supersteps of a PRO-algorithm (attribute F1) gives the expression $p = O(\sqrt{(\mathrm{T}_{\mathcal{A}}(n)/\mathrm{Steps})})$ upon resolving, and since $\mathrm{Steps} \geq 1$ holds,

the expression reduces to $p = O(\sqrt{\mathrm{T}_{\mathcal{A}}(n)})$. Moreover, since we may reasonably assume that all memory is initialized, the inequality $\mathrm{T}_{\mathcal{A}}(n) \geq \mathrm{S}_{\mathcal{A}}(n)$ holds. Thus the bound $p = O(\sqrt{\mathrm{S}_{\mathcal{A}}(n)})$ set by attributes B and C is more restrictive and the result follows. □

Since a PRO-algorithm yields linear speedup for every $p = O(\mathrm{Grain}(n))$, a result like Brent's scheduling principle is implicit for these values of p. But Observation 1 shows that we cannot start with an arbitrary number of processors and efficiently simulate on fewer processors. So Brent's scheduling principle does not hold with full generality in the PRO model, which is in accordance with practical observations.

We note that there exists a slightly similar notion to $\mathrm{Grain}(n)$ in the literature. This notion, called *iso-efficiency* function, is suggested as an analytical tool for evaluating the scalability of a parallel system (parallel algorithm together with a parallel architecture) [25, 26]. The iso-efficiency function, which is defined only for scalable algorithms, determines the ease with which a parallel system achieves speedups increasing in proportion to the number of processors involved. A small iso-efficiency function implies that a small increase in problem size is sufficient for the efficient utilization of an increasing number of processors, indicating that the parallel system is highly scalable. A large iso-efficiency function, on the other hand, indicates a poorly scalable parallel system. Thus, the iso-efficiency function, which is expressed as a function of p, is in a sense "inversely" related to $\mathrm{Grain}(n)$ in PRO. Despite this slight resemblance, the two notions are fundamentally different. $\mathrm{Grain}(n)$ is an attribute of a model; it is in fact a quality measure for a PRO-algorithm. The iso-efficiency function is not related to any computation model. Moreover, it is not always possible to get an analytic expression for the iso-efficiency function, even if the parallel algorithm is highly scalable in practice [25].

The design of a PRO-algorithm may sometimes involve subroutines for which no sequential counterparts exist. Examples of such tasks include communication primitives such as broadcasting, data (re)-distribution routines, and load balancing routines. Such routines are often required in various parallel algorithms. With a slight abuse of terminology, we call such parallel routines PRO-algorithms if the overall computation and communication cost is linear in the input size to the routines.

TABLE II

COMPARISON OF PARALLEL COMPUTATIONAL MODELS

	PRAM [12]	QSM [27]	BSP [4]	LogP [24]	CGM [16]	PRO
synch.	lock-step	bulk-synch.	bulk-synch.	asynch.	asynch.	asynch.
memory	sh.	sh.	dist.	dist.	priv.	priv.
commun.	SM	SM	MP	MP	MP/SM	MP/SM
parameters	n	p, g, n	p, g, L, n	p, g, l, o, n	p, n	$p, n, \mathcal{A}$
granularity	fine	fine	coarse	fine	coarse	Grain(n)
speedup	NA	NA	NA	NA	NA	$\Theta(p)$
optimal	NA	NA	NA	NA	NA	rel. $\mathcal{A}$
quality	time	time	time	time	rounds	Grain(n)

IV. COMPARISON WITH OTHER MODELS

In this section we compare the PRO model with PRAM, BSP, LogP, CGM, and the Queuing Shared Memory (QSM) model [27]. The QSM model is interesting since it is a shared memory model based on some BSP principles. Our tabular format for comparison is inspired by a similar presentation in [27]. The columns of Table II are labeled with names of models and some relevant features of a model are listed along the rows.

The synchrony assumption of a model is indicated in the row labeled *synch.* Lock-step indicates that processors are fully synchronized at each step (of a universal clock), without accounting for synchronization. Bulk-synchrony indicates that there can be asynchronous operations between synchronization barriers. The row labeled *memory* shows how a model views the memory of the parallel computer: 'sh.' indicates globally accessible shared memory, 'dist.' stands for distributed memory and 'priv.' is an abstraction for the case where the only assumption is that each processor has access to private (local) memory. In the last variant the whole memory could either be distributed or shared. The row labeled *commun.* shows the type of interprocessor communication assumed by a model. Shared memory (SM) indicates that communication is effected by reading from and writing to a globally accessible shared memory. Message-passing (MP) denotes the situation where processors communicate by explicitly exchanging messages in a point-to-point fashion. The MP abstraction hides the details of how the message is routed through the interprocessor communication network.

The parameters involved in a model are indicated in the row labeled *parameters*. The number

of processors is denoted by p, n is the input size, $\mathcal{A}$ is the reference sequential algorithm, l is the communication cost (latency), L is a single parameter that accounts for the sum of latency (l) and the cost for a barrier synchronization, *i.e.* the minimum time between successive synchronization operations, g is the bandwidth gap, and o is the overhead associated with sending or receiving a message. Note that the machine characteristics l and o are taken into account in PRO, even though they are not explicitly used as parameters. Latency is taken into consideration since the length of a superstep is determined by the sum of the computational and communication cost. Communication overhead is hidden by the PRO-requirement that number of supersteps is bounded by $O(\frac{\mathrm{T}_{\mathcal{A}}(n)}{p^2})$.

The row labeled *granularity* indicates whether a model is fine-grained, coarse-grained or a more precise measure is used. We say that a model is coarse-grained if it applies to the case where $n \gg p$ and call it fine-grained if it relies on using up to a polynomial number of processors in the input size. In PRO granularity is exactly the quality measure Grain(n), and appears as one of the attributes of the model.

The rows labeled *speedup* and *optimal* indicate the speedup and resource optimality requirements imposed by a model. Whenever these issues are not directly addressed by the model or are not applicable, the word 'NA' is used. Note that these requirements are 'hard-wired' in the model in the case of PRO. The label 'rel. $\mathcal{A}$' means that the algorithm is optimal relative to the time and space complexity of $\mathcal{A}$. We point out that the goal in the design of algorithms using the CGM model [5, 16] is usually stated as that of achieving optimal algorithms, but the model *per se* does not impose an optimality requirement.

The last row indicates the *quality* measure of an algorithm designed using the different models. For all other models except CGM and PRO, the quality measure is runtime. In CGM, the number of supersteps (rounds) is usually presented as a quality measure. In PRO the quality measure is granularity, one of the features that makes PRO fundamentally different from all existing parallel computation models.

V. Algorithm Design in PRO

In this section we use three examples to illustrate how the PRO model is used to design efficient parallel algorithms. In each example, we start with a specific sequential time and space complexity, and then design and analyze a parallel algorithm relative to these.

Our first example is the standard matrix-matrix multiplication algorithm with three nested for-loops. This example is chosen for two reasons: its simplicity and its suitability to emphasize the importance in PRO of explicitly stating the sequential time and space complexity against which a parallel algorithm is compared. The complexity of an optimal sequential matrix multiplication algorithm is still unknown, and many algorithms that are theoretically known to be faster than the standard cubic-time algorithm are impractical.

Our second example is list ranking, a basic routine used in many parallel graph algorithms. List ranking is an interesting example in our context as a CGM-analysis of one of its parallel algorithms suggests inefficiency, despite the fact that the algorithm is efficient in practice. The third example is sorting. This example has a known BSP algorithm that also satisfies all of the requirements of the PRO-model. The parallel algorithms for list ranking and sorting discussed here will be used in the experimental study reported in the next section.

A. *Matrix multiplication*

Consider the problem of computing the product C of two $m \times m$ matrices A and B (input size $n = m^2$). We want to design a PRO-algorithm relative to the standard sequential matrix multiplication algorithm $\mathcal{M}^3$ which has $\mathrm{T}_{\mathcal{M}^3}(n) = O(n^{\frac{3}{2}})$ and $\mathrm{S}_{\mathcal{M}^3}(n) = O(n)$.

We assume that the input matrices A and B are distributed among the p processors $P_0, ..., P_{p-1}$ so that processor P_i stores rows (respectively columns) $\frac{m}{p} \cdot i + 1$ to $\frac{m}{p} \cdot (i+1)$ of A (respectively B). The output matrix C will be row-partitioned among the p processors in a similar fashion. Notice that with this data distribution each processor can, without communication, compute a block of $\frac{m^2}{p^2}$ of the $\frac{m^2}{p}$ entries of C expected to reside on it. In order to compute the next block of $\frac{m^2}{p^2}$ entries, processor P_i needs the columns of matrix B that reside on processor P_{i+1}. In each superstep the processors in the PRO algorithm will therefore exchange columns in a round-robin fashion and then each will compute a new block of results. Note that each column exchanged in a superstep constitutes one single message. Note also that the initial distribution of the rows of matrix A remains unchanged. In Algorithm 1, we have organized this sequence of computation and communication steps in a manner that meets the requirements of the PRO model.

Algorithm 1 has p supersteps (Steps = p). In each superstep, the time spent in locally computing each of the m^2/p^2 entries is $\Theta(m)$ resulting in local computing time $\Theta(m^3/p^2) = \Theta(n^{\frac{3}{2}}/p^2)$ per superstep. Likewise, the total size of data (words) exchanged by each processor in a superstep

Algorithm 1: Matrix multiplication

Input: Two $m \times m$ matrices A and B. The rows (columns) of A (B) are divided into m/p contiguous blocks, and stored on processors $P_0, P_1, \ldots P_{p-1}$, respectively.

Output: The product matrix C where the rows are stored in contiguous blocks across the p processors.

for *superstep* $s = 1$ *to* p **do**

  foreach *processor* P_i **do**

    P_i computes the local sub-matrix product of its rows and current columns;

    $P_{(i+1) \ mod \ p}$ sends its current block of columns to P_i;

    P_i receives a new current block of columns from $P_{(i+1) \ mod \ p}$;

is $\Theta(m^2/p) = \Theta(n/p)$. Thus, the length of a superstep σ is $\mathrm{T}_\sigma(n,p) = \Theta(n^{\frac{3}{2}}/p^2 + n/p)$. Note that for $p = O(\sqrt{n})$, $\mathrm{T}_\sigma(n,p) = \Theta(n^{\frac{3}{2}}/p^2)$. Hence, for $p = O(\sqrt{n})$, the overall parallel runtime of the algorithm is

$$\mathrm{T}(n,p) = \sum_{\text{Steps}} \Theta(n^{\frac{3}{2}}/p^2) = \Theta(n^{\frac{3}{2}}/p) = \Theta(\mathrm{T}(n)/p). \tag{4}$$

Noting that $\mathrm{S}(n) = \Theta(n)$, we see that the memory restriction of the PRO model is respected, *i.e.*, each processor has enough memory to handle the transactions. In order to be able to neglect communication overhead, the condition F1 on the number of supersteps, which in this case is just p, should be met. In other words, we need to choose p such that $p = O(\mathrm{T}_{\mathcal{A}}(n)/p^2) = O(n^{\frac{3}{2}}/p^2)$, which is true for $p = O(\sqrt{n})$. The optimality requirement F2 is satisfied as we have already shown in Equation 4 and thus the granularity function of the PRO-algorithm is $\mathrm{Grain}(n) = O(\sqrt{n})$.

Observe that in any such analysis the sequential reference algorithm, which in this case is $\mathcal{M}^3$, can be replaced by any other algorithm $\mathcal{A}$ that observes the same complexity bounds. The following lemma summarizes this result.

Lemma 1: Multiplication of two $\sqrt{n} \times \sqrt{n}$ matrices has a PRO-algorithm with $\mathrm{Grain}(n) = O(\sqrt{n})$ relative to a sequential algorithm $\mathcal{A}$ with $\mathrm{T}_{\mathcal{A}}(n) = O(n^{\frac{3}{2}})$ and $\mathrm{S}_{\mathcal{A}}(n) = O(n)$.

From Observation 1, we note that Algorithm 1 has optimal grain. Note that on a relaxed model, where the assumption that $p \leq M$ is not present, the strong regularity of matrix multiplication and

the exact knowledge of the communication pattern allow for algorithms that have an even larger granularity than $\sqrt{n}$. For example, a systolic matrix multiplication algorithm has a granularity of n. However, PRO is intended to be applicable for general problems (including those with irregular communication pattern) and practically relevant parallel systems.

B. List Ranking

In the *list ranking* problem (LR) we are given a vector $\texttt{next}[1..n]$ representing a linked list of n elements and a vector $\texttt{length}[1..n]$ with $\texttt{length}[i]$ the 'length' of the link from element i to element $\texttt{next}[i]$. For each element i we want to compute the sum of lengths of all links from element i to the end of the list. There is a trivial linear time sequential algorithm and it is a classical question from the early days of parallel computing to find a good parallel algorithm (see for example [28, 29, 30]). One parallel solution for LR uses the well-known technique of *pointer jumping*, see Algorithm 2. This algorithm has $\log n$ phases and is based on the simple observation that in a directed graph where each node i has a single outgoing arc $\texttt{next}[i]$ we can in a single phase halve the diameter of the graph, by 'pointer jumping' which entails setting $\texttt{next}[i] \leftarrow \texttt{next}[\texttt{next}[i]]$ in parallel for all nodes.

Algorithm 2: List Ranking using Pointer Jumping

Input: Ground Set V and vectors $\texttt{next}[1..n]$ and $\texttt{length}[1..n]$, with indices/elements distributed evenly among p processors

Output: Vector $\texttt{length}[1..n]$ with $\texttt{length}[i]$ the sum of lengths from i to end of next list

for *phase* $s = 1$ *to* $\log n$ **do**
  foreach *processor* P_j **do**
    foreach *element* v *belonging to* P_j **do**
      $\texttt{length}[v] \leftarrow \texttt{length}[v] + \texttt{length}[\texttt{next}[v]]$
      $\texttt{next}[v] \leftarrow \texttt{next}[\texttt{next}[v]]$

This algorithm is easily translated into a CGM or PRO algorithm where phases correspond to supersteps in which the processors communicate their respective values $\texttt{length}[\texttt{next}[i]]$ and $\texttt{next}[\texttt{next}[i]]$. There are of course some details in doing this: each processor must first send a request to those processors that store a $\texttt{next}[i]$ index whose values it needs, secondly receive

similar requests for values from other processors, thirdly send the values requested from it and finally receive the values it requested. The number of supersteps is $O(\log n)$ (or $O(\log p)$ after some refinement). In any case, the number of supersteps reflects a super-linear computation cost for the entire algorithm, which captures very well the fact that this algorithm is not efficient.

There are more sophisticated parallel algorithms for LR that are efficient, even when compared to the linear-time sequential algorithm. One class of such algorithms is known as '*independent set*' or 'k*-ruling set*' algorithms, another class is known as '*dominating set*' algorithms. Their analysis in terms of CGM or PRO is similar, here we will only briefly present an 'independent set' algorithm, see Algorithm 3.

Algorithm 3: Recursive List Ranking

Input & Output: Groundset V and vectors `next` and `length` as in Algorithm 2

if *input list size is small* **then** solve by Pointer Jumping;

else

- With a suitable PRO-algorithm, find a maximal independent set I in the input list;
- **foreach** *element* $v \in V$ **do**
  - compute $\texttt{next}_I[v]$, the closest successor of v in I;
  - compute $\texttt{length}_I[v]$, the sum of lengths from v to $\texttt{next}_I[v]$;
- Recursive List Ranking$(I, \texttt{next}_I, \texttt{length}_I)$;
- Propagate the partial solution found for I to elements in V that are not in I

This algorithm is recursive and starts by computing a large independent set I of nodes (having the property that if $i \in I$ then $\texttt{next}[i] \notin I$), for example by a variant of a so-called *random mating* algorithm. This set can be guaranteed to be maximal and thus of size εn, for $\frac{1}{3} \leq \varepsilon \leq \frac{1}{2}$. We then compute for each $i \in I$ the value $\texttt{next}_I[i] \in I$ which is its closest successor in the linked list and the accumulated distance from i to that element, $\texttt{length}_I[i]$. When coming back from the recursion with a solution for this intermediate list I, it is not difficult to propagate the information that is obtained to the elements that were not in I.

The translation of such algorithms to CGM is usually straightforward and the analysis with CGM is simple. Obviously, the recursion introduces a logarithmic number of supersteps and hence the total processing cost *in terms of the CGM model* is super-linear.

However, the overall work in each recursion level can be made linear in the actual size of the

list and so the work load decreases with every step of the recursion. Since the auxiliary list for the recursion is substantially smaller than the original list (εn), a geometric series argument can be applied to show that the overall resource utilization is linear. Hence, contrary to what a CGM-analysis suggests, this second family of algorithms is in fact efficient. Thus the LR example exhibits a case where a CGM-analysis is not able to distinguish between a "bad" algorithm (Algorithm 2) and a "good" one (Algorithm 3).

The PRO model provides a different view of Algorithm 3. Assuming that the chosen independent set at each recursion level is well balanced among the processors, it is easy to show that $\mathrm{T}(n,p) = \Theta(n/p) = \Theta(\mathrm{T}_{\mathcal{A}}(n)/p)$. In order to be able to neglect communication overhead, we need to meet the condition F2 on the number of supersteps $\log n$. This means we need $\log n = O(\frac{n}{p^2})$, which upon resolving gives $p = O(\sqrt{\frac{n}{\log n}})$. With $\mathrm{S}(n) = \Theta(n)$, the PRO memory restriction is respected.

The following lemma summarizes these results.

Lemma 2: List ranking on n elements has a PRO-algorithm with $\mathrm{Grain}(n) = O(\sqrt{\frac{n}{\log n}})$ relative to a sequential algorithm $\mathcal{A}$ with $\mathrm{T}_{\mathcal{A}}(n) = O(n)$ and $\mathrm{S}_{\mathcal{A}}(n) = O(n)$.

Note that the granularity function in this PRO-algorithm is less than $O(\sqrt{n})$ and thus the granularity is not optimal.

C. Sorting

Like list ranking, sorting problems occur frequently in sequential as well as distributed computing. For our experimental studies, we chose the randomized and distributed sorting algorithm described in [31] in the context of the BSP model. The algorithm is based on an over-sampling technique, and is outlined in Algorithm 4.

Algorithm 4 starts by computing a small random sample of the items that are to be sorted (phase Φ_1). Then, that random sample is used to determine $p-1$ *splitters* that are approximately equidistant in the set of sorted items (phase Φ_2). The splitters can be seen as a generalization of the computation of a p-median. In fact, for $p = 2$ the (unique) splitter is expected to be close to a median value. The splitters are then used by the processors to partition their values into p different buckets (phase Φ_3), and to redistribute them to appropriate target processors (phase Φ_4). The algorithm terminates with a parallel local sorting on all processors (phase Φ_5).

Algorithm 4: Parallel Sorting

Input: $0 \leq \rho < p$ a number identifying this processor, A a distributed array of values, A_ρ corresponds to the local sub-array for the current processor

Output: The A array is globally sorted.

begin

Φ_1 Randomly extract a sample E_ρ of k values from A_ρ;

Send the sample E_ρ to Processor P_0;

if $\rho = 0$ **then**

  $E \leftarrow \bigcup_{0 \leq i < p} E_i$;

Φ_2 local_sort(E);

  Create an array of splitters S and set $S[0] = -\infty$ and $S[p] = +\infty$;

  foreach $i = 1, \ldots, p-1$ **do** $S[i] \leftarrow E[i \times k]$;

  Broadcast S to all the other processors;

Receive the splitters S from Processor P_0;

Φ_3 **foreach** *Value* $v \in A_\rho$ **do**

  find ℓ with $S[\ell] \leq v < S[\ell + 1]$;

  $M_\ell \leftarrow M_\ell \cup \{v\}$;

Φ_4 **foreach** $i = 0, \ldots, p-1$ **do**

  Send M_i to Processor P_i;

foreach $i = 0, \ldots, p-1$ **do**

  Receive array M'_i from processor P_i;

Φ_5 $A_\rho \leftarrow \bigcup_{0 \leq i < p} M'_i$;

local_sort(A_ρ);

end

The performance of Algorithm 4 depends on the choice of a value k for the size of the local sample that is computed in phase Φ_1. The choice of k has to ensure that the overall sample is a good representative of the input array such that the final share of data for each processor that is to be received in phase Φ_4 and to be sorted in phase Φ_5 is not too large.

To simplify analysis, we choose $k = n/p^2$. For more subtle discussions on the requirements for the choice of k that guarantees a good expected behavior see [31, 32].

We will now look at the complexity of each of the five phases in Algorithm 4.

Φ_1**:** This phase can be done in $O(m)$ time, where $m = n/p$.

Φ_2**:** Since the sample size that processor P_0 has to handle is $pk = n/p = m$ the computation cost of this phase is at most $O(\mathrm{T}_{\mathcal{A}}(m))$.

Φ_3**:** If we use binary search to determine the bucket for each element, this phase can be done in $O(m \log(p))$ time.

Φ_4**:** This phase is by far the most expensive task in terms of communication: the initial global array A (size n) is completely redistributed through the interconnection network. So this phase accounts for $O(m)$ in the PRO-complexity.

Φ_5**:** Assuming that the first three phases provide a balanced redistribution of the initial array ($\Theta(m)$ values per processor), the computation cost of this phase is again $O(\mathrm{T}_{\mathcal{A}}(m))$.

Thus the overall computation cost of Algorithm 4 is $O(\mathrm{T}_{\mathcal{A}}(m) + m \log(p)))$, and because of the lower bound of $\Omega(n \log n)$ for comparison sorting this is $O(\mathrm{T}_{\mathcal{A}}(m))$. Since we may also assume that $\mathrm{T}_{\mathcal{A}}(n)$ is a non-concave function we have that $\mathrm{T}_{\mathcal{A}}(m) = O(\mathrm{T}_{\mathcal{A}}(n)/p)$ and thus the speedup relative to $\mathcal{A}$ is $\Omega(p)$. The overall communication volume required by the algorithm is bounded by $O(n)$.

Since the number of supersteps of the algorithm is also bounded by a constant, this algorithm fulfills all of the PRO-requirements and in fact has optimal granularity.

Lemma 3: Sorting of n elements has a PRO-algorithm with Grain$(n) = O(\sqrt{n})$ relative to any comparison-based sequential algorithm $\mathcal{A}$ with $\mathrm{T}_{\mathcal{A}}(n) = \Omega(n \log n)$ and $\mathrm{S}_{\mathcal{A}}(n) = O(n)$.

VI. Experimental Validation

The aim of this section is to provide experimental evidence to help validate the PRO model. To be convincing, an experimental set up for validating a computational model needs to fulfill several criteria. Among others it should:

- cover a sufficiently large selection of algorithms, inputs, and platforms;
- address the practical aspects of the model;
- be reproducible.

Moreover, a parallel implementation needs to be compared with a good quality *sequential* implementation to justify its usefulness. The latter criterion is often hard to satisfy. In several cases in the literature, such as in [33], parallel algorithms that appear attractive due to their

TABLE III

PLATFORMS CONSIDERED IN OUR EXPERIMENTS

Platform name	Type	Nr. Proc.	Freq. (MHz)	Memory (GiB)	Network type	Bandwidth Mb/s	OS
SGI Origin3000	DSM ccNUMA	56	700	42	SGI NUMA-Link		IRIX
SunFire 6800	DSM ccNUMA	24	900	24	Sun Fireplane Interconnect		Solaris
Icluster	Cluster	200	733	51.2	Ethernet	100	Linux
Albus	SMP Cluster	16	1333	8	Ethernet Myrinet	100 4000	Linux

relative performance as the number of processors is varied, turn out to be several orders of magnitude slower when compared to a pure sequential algorithm.

The experimental set up we used, which will be described shortly, has been successfully applied on a large variety of algorithms, including algorithms for matrix multiplication (using BLAS routines), combinatorial problems on trees and lists, sorting, and problems on large cellular networks [2, 35, 36]. For the purpose of illustrating the usefulness of the PRO model, here, we focus on only two of these algorithms. In particular, we report results on the list ranking and sorting algorithms discussed in the previous section (Algorithms 3 and 4, respectively).

The list ranking and sorting problems were chosen since they are good representatives of two different classes of problems: list ranking uses a highly irregular data structure (linked list) and sorting uses a highly regular data structure (array). In general the relative communication cost associated with irregular data structures is higher than that associated with regular data structures.

A. *Experimental setting*

Both the list ranking and sorting algorithms were implemented using *SSCRAP* [10, 11]. *SSCRAP* (Soft Synchronized Computing in Rounds for Adequate Parallelization) is a C++ communication and synchronization library for implementing coarse-grained parallel algorithms on different platforms, including clusters and parallel machines. In addition to the PRO model, *SSCRAP* supports all known flavors of “coarse-grained models”. By providing a high level of

abstraction, *SSCRAP* makes complex communication tasks transparent to the user and handles inter-process data exchanges and synchronization efficiently.

Due to its efficiency, low overhead, and architecture-independence, *SSCRAP* can be used to carry out a reliable experimental study for the validation of coarse-grained models. Recently, *SSCRAP* has been integrated into `parXXL`, a software suite that provides facilities for implementing algorithms for large scale simulations that are modeled in terms of cellular networks [34, 35].

In our experiments we considered four variants of platforms. The main features of these platforms are summarized in Table III. Starting with the leftmost column, the table lists the platform name, the architecture type, the number of available processors, the processor frequency, the total memory size, the interconnection type, the communication bandwidth and the operating system used in each case. We used two essentially different types of platforms: distributed-shared-memory (DSM) parallel machines and clusters. For DSM, we used two different 64 bit machines. The first one is an SGI Origin 3000 and the second is a SunFire 6800. In addition, we experimented with the SGI machine using two different sets of processors, the first of type R 12000 and the second of type R 16000. We refer to these as R12M and R16M, respectively.

Table III also presents two different clusters, named Icluster and Albus. Icluster is a large PC cluster with about 200 common desktops powered by PIII processor. Albus is a cluster composed of 8 biprocessor-AMD Athlon MP SMP nodes. Albus has two different interconnections, a standard 100 Mb/s switched Ethernet and a high speed Myrinet.

B. Experimental Results

We have carried out extensive experiments on the different platforms using a wide range of input sizes for the two test problems. Here we present a few results that are most relevant to validating the PRO model. A more detailed account of the experimental study is available in [36].

1) Execution time: Figures 1(a) and 1(b) show execution time plots for the list ranking and sorting algorithms, respectively. The plots are on log-log scale, where the horizontal axis corresponds to *number of processors* and the vertical axis to *normalized execution times* per *number of items*. The term "number of items" here is a generic description for the number of list elements in the list ranking algorithm or the number of elements to be sorted in the sorting algorithm. The curves in Figure 1 show results for the *largest* number of items we were able to

solve on the various platforms. To be able to compare behaviors across different architectures, the execution times have been normalized by the CPU frequency; thus the normalized quantities appear as clock cycles of the underlying architecture. In some sense this normalization also hides efficiency-differences across the platforms that would have appeared if pure running times were to be used. Should the actual runtimes be of interest, they can easily be obtained using the clock frequencies given in Table III.

For each four-tuple (algorithm, platform, number of items, number of processors), the result shown in Figure 1 is an average of 10 runs. In these runs, the variance was consistently observed to be very low. On the DSM machines, the execution times on one processor correspond to the execution times of an optimized *sequential implementation* and not to those of the parallel algorithm run on a single processor. Hence, the speedups observed on these machines are absolute, as opposed to relative. On the clusters, problem instances of the sizes reported here could not be solved on a single machine. Hence, sequential runtimes are not available for comparison on these platforms (the corresponding curves in Figure 1 start at a number of processors larger than one).

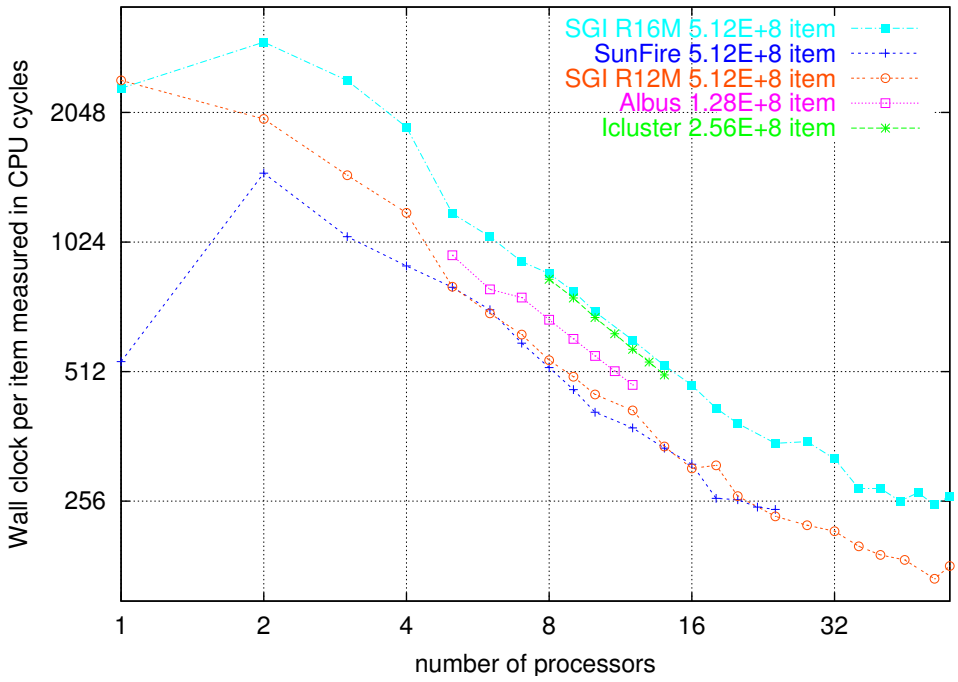
The following observations can be made from Figure 1.

- The curves are to a large extent close to straight lines, indicating that the speedup is linear over a wide range of processors.
- A comparison between the execution time of the optimal sequential algorithm (the case where $p = 1$) and the parallel runtime on two processors reveals that the overhead for parallelization on almost all the architectures considered is relatively small.
- The execution time curves are nearly parallel to each other.
- For both the list ranking and sorting algorithms, the behavior is remarkably similar on the various platforms.

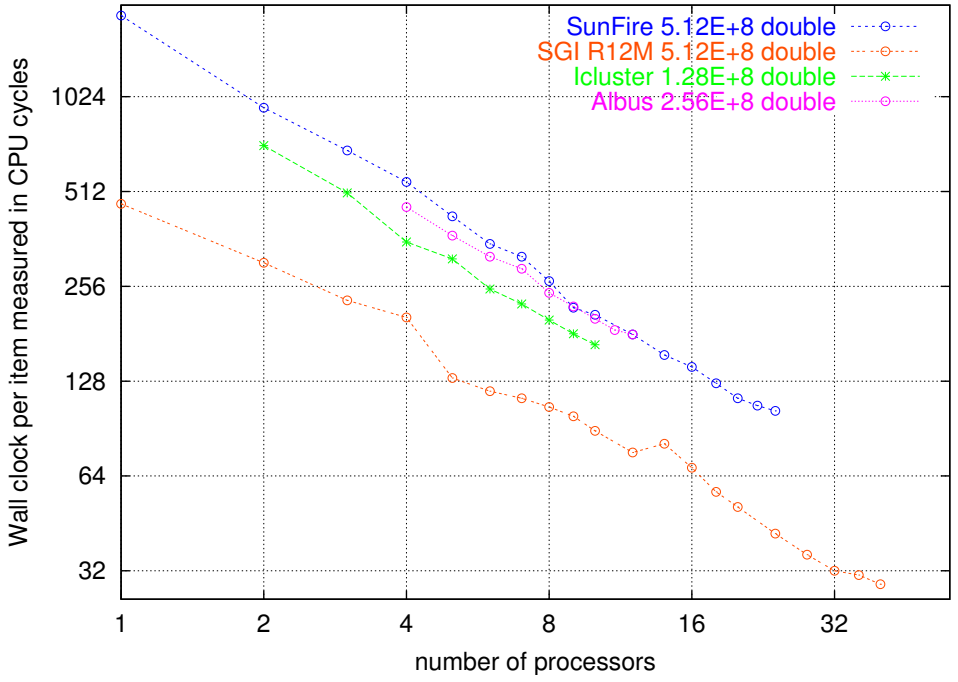
2) Memory usage: Let N_{seq} be the maximum input size (for the list ranking or the sorting algorithm) that can be computed sequentially in memory of size M_{seq}. The corresponding PRO algorithms using p processors should then enable one solve inputs of size $\Omega(p \cdot N_{seq})$ in memory volume of $\Theta(p \cdot M_{seq})$.

To show that this behavior is observed in practice we present Figure 2. The figure shows the maximum input size that could be computed on the platform ICluster, for both the list ranking and the sorting algorithms. Each node of the cluster has 256 MiB local memory and a sequential

Fig. 1. Computational Results on all platforms. Ideal speedup would correspond to curves of slope -1.

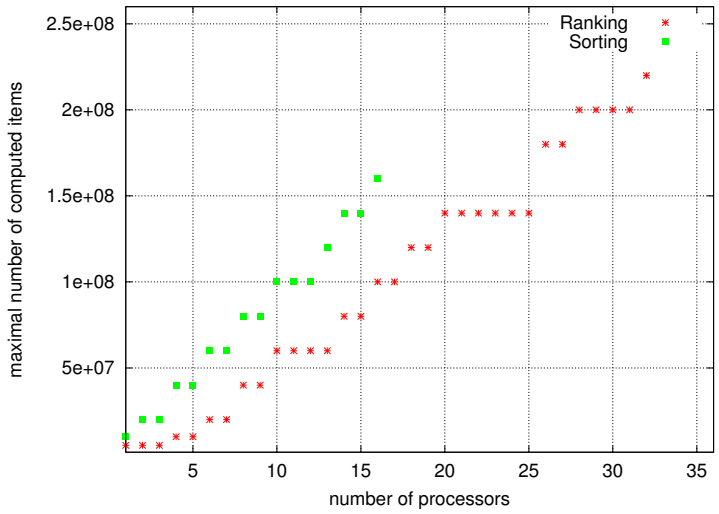


(a) List Ranking



(b) Sorting

Fig. 2. List Ranking and Sorting: Maximum input size computed on Icluster



version of the list ranking algorithm could only rank 5 million elements (resp. 10 million doubles for sorting). For the parallel PRO algorithm, by employing more nodes, larger input sizes could be computed. Figure 2 shows that, disregarding irregularities due to discretization, the maximum input sizes to the PRO algorithms scale linearly for a wide range of processors. Figure 2 also shows that sorting scales slightly better than list ranking. This is due to the recursion involved in and the memory overhead associated with the independent set construction in the list ranking algorithm; both of these aspects make the list ranking algorithm require more memory than the sorting algorithm.

VII. Conclusion

We have introduced a new parallel computation model (called PRO) that enables the development of efficient and scalable parallel algorithms and simplifies their complexity analysis.

The distinguishing features of the PRO model are the novel focus on relativity, resource-optimality, and a new quality measure (granularity). In particular, the model requires a parallel algorithm to be both time- and space-optimal relative to an underlying sequential algorithm. Having optimality as a built-in requirement, the quality of a PRO-algorithm is measured by the maximum number of processors that could be used while the optimality of the algorithm is maintained.

The focus on relativity has theoretical as well as practical justifications. From a theoretical point of view, the performance evaluation metrics of a parallel algorithm includes speedup and optimality, both of which are always expressed relative to some sequential algorithm. In practice, a parallel algorithm is often developed based on some known sequential algorithm. The fact that optimality is incorporated as a requirement in the PRO model enables one to concentrate only on parallel algorithms that are practically useful.

However, the PRO model is not just a collection of some 'ideal' features of parallel algorithms, it is also a means for achieving these. In particular, the attributes of the model capture the salient characteristics of a parallel algorithm that make its practical optimality and scalability highly likely. In this sense, it can also be seen as a parallel algorithm design scheme. We believe the experimental results reported in this paper go some distance in justifying this claim.

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