Bull. Nov. Comp. Center, Comp. Science, 17 (2002), 1–8

Fifteen years of the Supercomputer Software Department

V.E. Malyshkin

The Supercomputer Software Department (SSD) of the Computing Center SB RAS (at present Institute of Computational Mathematics and Mathematical Geophysics), Novosibirsk, was founded on April 1, 1987 on the base of System Software Laboratory and Research Group of Parallel Program Synthesis. The goal of this alliance was the actualization of integrated theoretical and applied studies in various areas of parallel computations. Here it is necessary to keep in mind that the Computing Center of SB RAS is a big complex institute. It consists of 11 departments: theoretical and applied geophysics, mathematical modeling, mathematical simulation of processes in hydrodynamics, statistical modeling in physics, etc. One of the major objectives of the SSD work is the support of scientific work of these departments with parallel computing technologies, and so the problems of these departments are the main source of our applications.

The first important result was the creation of computer system "Siberia" in 1989. The system represents a large-block computer complex on the basis of ES computer components and its parallel system software (parallel extension of the operating system, parallel programming language and compiler). The components of the complex were the control computer ES-1068 and 8 attached processors ES-1027 with rather good for that time peak efficiency – 100 Mflop. "Siberia" was designed for parallel implementation of large-scale problems in physics and first in seismic data processing.

Our research is concentrated in the following main areas: formal models of parallel computations, parallel architectures, parallel languages and programming systems, parallel program synthesis, computations organization on MIMD multicomputers, parallel solution of large-scale problems, cellular and cellular-neural computations, parallel computing technologies. This variety of subjects is supported and encouraged in the department in order to accumulate the critical mass of results necessary for creating of the modern computing technologies. Like any practical activity, the development of parallel computing technologies requires a complex approach to proper implementation, and due to this reason technologies combine various theoretical and experimental studies.

In parallel computing there are two types of parallelism: coarse-grain and fine-grain. Both are under study at the department.

The coarse-grain parallelism is studied within the project of development of the assembly technology of parallel programming, which is aimed at the design of a parallel programming system for multicomputers, first of all oriented to supporting the development of large-scale numerical models. Mathematical foundation of the assembly technology is the structural method of parallel program synthesis.

Main problems of parallel programs development (sequential programs parallelization) for multicomputers are well-known. First, any good parallel program should possess several new necessary general properties: nondeterminism of execution, flexible tuning to all the available resources, portability in the class of multicomputers, dynamics of behavior, high reliability. These properties were not required (or their absence do not seem to be crucial) for sequential programs.

Another problem is the allocation of multicomputer resources (including time) to provide their uniform workload (mapping of the application algorithm on multicomputer resources). In the case when independently running processes require essentially different amount of resources there is, generally, no good allocation. In addition, the amount of necessary resources becomes available in most cases only in the course of execution of a program, before the start of computations there is usually no such information.

The solution of these problems (parallelization of a sequential one) can be found on the way of development of "fine" fragmented programs, whose fragmentation is kept in the course of computation. Each fragment of a code defines a process. In this case the following two conditions should be fulfilled:

- all the processes should require approximately an equal amount of resources and
- on a set of all the processes a partial order should exist so that all the processes interact only with their neighbors.

Explicit numerical algorithms on rectangular grids are an example of algorithms allowing such a representation and frequently (but not always!!) implemented well enough on multicomputers in the ordinary way. Computations inside one cell, or computations inside one string or a layer of cells stand for fragments.

In a parallel program designed under the assembly technology, the behavior of a system of processes executed in parallel and interacting with each other is organized in such a way that their behavior in multicomputer looks like the behavior of a liquid in a system of "communicating vessels": if one processor becomes overloaded, then the overload flows to the adjacent (connected with physical links) processors. So, the allocation of the high quality resources is achieved as well as flexible tuning of a parallel program to all the available resources, and the code portability within the class of

multicomputers. An assembled program may know nothing on the structure of the multicomputer's communication network and will be very stable against various hardware failures. For implementation of this behavior dynamics, a number of diffusion algorithms for the dynamic load balancing were designed.

The assembly technology was applied to the design of the universal parallel code implementing the Particles-In-Cells method (PIC) in its applications to modeling of different phenomena in plasma physics. The program was ported with no performance loss to multicomputers Parsytec, SP2, Cray T3D, iPSC-860, to cluster of workstations.

The technology of parallel programs assembly is well described in non-procedural high-level languages and even in visual programming languages, in which a problem formulation is painted and an efficient program is assembled from composite samples. In this way, the system for automatic generation of parallel programs implementing numerical algorithms on rectangular grids was designed as well as the system for assembly of program visualizing the course and results of numerical modeling.

The idea of fine-grain parallelism ascends to von Neumann works who, in the middle of the past century, offered a model of cellular automata. It is the model of a biocenosis consisting of a set of cells located in a metric space and interacting only with the same cells from their neighborhood. All the cells perform their functions concurrently thus simulating the spatial dynamics of a certain natural phenomenon. Even at this level it has become quite clear that a huge number of simple cells acting in cooperation can simulate very complex processes.

The cellular automaton gained in practical importance later, when the development of microelectronics started, and there appeared a hope of its implementation on chip. At that time a generalization of the model appeared in the form of programmable tunable cellular systems called "computation media". This direction was intensively developed in the Institute of Mathematics SB RAS in 1960–1970, where from it came (with a group of researchers) to our Department. Here, on the basis of the already gained experience, a formal theory of cellular computations was worked out – the Parallel Substitutions Algorithm (PSA), which is intensively employed for description, transform, and design of multi-purpose cellular algorithms.

The PSA has appeared as a result of the search for an efficient mathematical basis for design and study of fine-grain algorithms and architectures. Conceptually, the PSA unites substitutional nature of Markov algorithm with spatial parallelism of the cellular automata based on their common associative mechanism of operation application. The PSA reflects the "natural parallelism" of computations: general and simultaneous application of commands (substitutions) to multidimensional data arrays, explicit indication to relations between data in commands. The theory includes results

of research for the behavior properties presented in the PSA form, definition of the conditions of their determinism and termination and, also, the equivalent time-space and structural transformations.

Within the proposed theory, the tools for the fine-grain computations simulation were designed, namely, the WinALT system. The WinALT system is built as an open system which is modified and appended by the user in the course of development of the fine-grain computations technology and extension of the area of its applications. It enables the implementation of the same given parallel algorithm in cellular architectures that differs in cellular space dimension, functional transformation performed by one cell, topology of the links between cells and operation mode with respect to time.

Synthesized and studied with the WinALT were the models of algorithms of fast parallel arithmetic (summation, complex number multiplication), image processing, neuron processor simulator, which are destined for employment in new generations of special processors. The construction of special processors for high-speed processing of huge arrays of information requires that the problem of interlinks in microelectronic structure be solved. The proposed methods for time-space and structural equivalent transformations of the PSA allow transition of special processor from the two-dimensional architecture to the three-dimensional ones which enables data pipelining by all three directions. Within this transition most intercellular links turn into interlayer links of the three-dimensional architecture with a significant simplification of each layer. These architectures suit well for implementation as electro-optical multilayer VLSI chips with simple topology of each layer and numerous optical interlayer links. As a promising class of the multilayer VLSI chips the a set of universal electro-optical matrices with the help of the WinALT system was studied. The matrices demonstrate the possibility to create high-performance computational devices by introduction of optical links into chip structure and by the use of a new component – a thin film light modulator. Estimates of the matrix structure were obtained, the method of pipeline computations organization was proposed, when a matrix is tuned to imitation of a pipeline mode operation not only of one chip, but of the whole set of chips.

Another direction in the development of the fine-grain parallelism is bound with the search for new mathematical models of nonlinear spatial dynamics (gas dynamics, phase transitions, chemical reactions). In the world-wide mass media, this direction is oriented to the creation of cellular-automata models and algorithms, implemented on the basis of the so-called Cellular-Automata Machines – programmable special processors of the cellular type. At our Department, the problem of creation of models and algorithms with fine-grain parallelism is set up essentially wider: we are planning to create models of nonlinear dynamics which would replace, to some extent, classical partial differential equations. Due to this reason we

associate the principles of neural networks operation and probability computations with the cellular-automata ideology. The first group enriches the model with the ability of "training" (Cellular-Neural Network) in order to simulate the processes not represented by differential equations. The second group allows representation of complex nonlinear phenomena combining discrete cellular-automata calculations with those of continuous functions in real domains.

The main motivation of this approach is the following:

1. Unlike numerical solution to differential equations, the fine-grain algorithms are free from the round-off errors and the difficulty of gaining the stability of computation process.
2. The fine-grain algorithms possess a good large-block parallelization ability, naturally fitting the assembly technology of parallel computations and admitting the dynamical load balancing between processors.

Three types of the fine-grain parallelism models are under study:

- cellular automata for simulating gas dynamics,
- cellular-neuron automata, and
- cellular-neuron nets of first and second order.

Cellular-automata for gas dynamics simulation (Gas-Lattice) is studied, and a 3D cellular automata model of viscous liquid flows is proposed, in which a grid such as polar complex rhombus-dodecahedron is used. To study the model properties, a program complex is created that is able to change parameters of the flux and to observe the process under simulation.

The Cellular-neuron automaton (CN-automaton) is an original model, which combines "cellular-automata diffusion" with a nonlinear function of a stochastic neuron. The CN-automaton can be used as an alternative for the reaction-diffusion differential equations. It is represented by a two-layer cellular structure, whose one layer (diffusive) acts as diffusive cellular automaton and the second layer (reaction) acts as cellular-neuron network. Modeling of typical reaction-diffusion processes (traveling fronts, Belousov–Zhabotinsky reaction) demonstrate the working efficiency of this model.

The Cellular-neuron networks (CNN) combine the properties of cellular automata (local interactions between the cells-neurons) and artificial neural networks (weighted connections, a nonlinear sigmoidal output function). Such a combination of properties allows its use as nonlinear models of spatial dynamics.

The first order CNNs (CNN-1) are described by the first order differential equations (continuous representation) or a one-layer cellular structure with local weight links (discrete representation). Two types of the first order CNNs were studied: nonhomogeneous with different templates of link

weights, and homogeneous in which all the cells have equal link weights. The non-uniform CNN can be used as associative memory. They are destined for storage of a number of images (global states of CNN-1) and for selection of one of them by noisy values on input. The uniform CNN-1 simulate the dynamics of spatial image formation. They can be used in research into ecology, mineralogy, and chemistry. For both CNN-1 types the learning algorithm (template weights definition) was designed which provides the formation by a given sample of an image of the same class. The cellular-neural networks of second order (CNN-2) simulate autowave processes like a traveling front, a traveling impulse, auto-oscillations, spiral-shaped waves, and various fancy autowave phenomena emerging in a two-component medium (chemical waves, ecological phenomena). A program package that enables the study of behavior properties of CNN-2 either on a sequential computer or on a multiprocessor system with message passing was developed.

To solve the problems of non-numerical information processing, the fine-grain parallel systems of the SIMD type are studied with vertical (or sequential digit-by-digit) processing. A model of the vertical processing system was built (STAR machine), and a formal scheme for graph problems solution on computers of this architecture was designed. A number of classical algorithms of graph theory were efficiently implemented on the vertical processing system. For non-oriented graphs these are the Prima–Dejkstra and the Kruskal algorithms for a minimum basic tree construction and the Gabov algorithm for a minimum basic tree search with constraints on the degree of a given node. For oriented graphs these are the Edmonds algorithm for optimal branching and the Bellman–Ford algorithm for the shortest ways definition from a node to all the other nodes.

The two polar models of the fine-grained and the coarse-grained parallel computations are not in conflict. Moreover, we try to "cross them over" and to develop a combined model and computing technologies based on it. The first results greatly encourage us.

The study of the computer science history – one of the greatest achievements of the twentieth century – is an important part of our research. The first result of this work was the book "Sketches on History of Computer Science in Russia". This is a book, in which materials and documents related to the first period of birth and development of cybernetics (computer science) in our country are gathered. This project is the winner of the Prize of the "Pushkin's Library" megaproject. In 2001, the books "Kolmogorov and Cybernetics" and "Alexei Andreevich Lyapunov" were published. In the first one, the unique materials were gathered that show the views of great mathematician and thinker A.N. Kolmogorov to cybernetics and his contribution to the development of this science. Published in the second one are the materials, documents and letters related, chiefly, to the Siberian period of life of "the creator of Russian cybernetics and programming", awardee of

the "Computer Pioneer" prize, A.A. Lyapunov.

Starting with the year of 1991, every odd year the Department organizes in Russia international conferences of the PaCT (Parallel Computing Technologies) series. In 2001, the sixth PaCT was held. It is planned to hold the next PaCT-2003 in Nizhny Novgorod. The objectives of this series of conferences are to unite the scientists working in theory, architecture, software, hardware, big problems solution, to enable the discussion of parallel computing technologies and to disseminate new results and technologies. Proceedings of the last conferences were published in Lecture Notes in Computer Science series (Springer-Verlag), volumes 964, 1277, 1662, and 2127. The selected papers accepted for the PaCT-99 were published in a special issue of the journal "Future Generation Computer Systems" (Elsevier, NH), Vol. 17 (2001) devoted to parallel computing technologies. A similar issue is planned for publishing on the basis of selected papers accepted for the PaCT-2001.

We could finish with a cheerful slogan: "fifteen to go ahead and win". If a more serious point of view is taken, programming as science as well as methods and tools of mathematical models implementation, gives more and more interesting problems and is not restricted within traditional languages and programming systems. Generally, the sphere of programming is significantly broadening.

References

[1] Achasova S., Bandman O. Correctness of Parallel Computational Processes. – Novosibirsk: Nauka, 1990.

[2] Bandman O. Fine-grained parallelism in computational mathematics // Programmirovanie. – 2001. – № 4. – P. 5–20 (in Russian).

[3] Bandman O. Cellular Neural Automaton. A Discrete Model for Active Media Dynamics. – http://www.sbras.ru/ws/Lyap2001/23-34 (in Russian).

[4] Valkovsky V., Malyshkin V. Synthesis of Parallel Programs and Systems on Computational Models. – Novosibirsk: Nauka, 1988.

[5] Kraeva M.A., Malyshkin V.E. Assembly technology for parallel realization of numerical models on MIMD-multicomputers // Future Generation Computer Systems. – 2001. – Vol. 17. – P. 755–765.

[6] Markova V., Piskunov S., Pogudin Yu. Formal methods, language and instrumental tools for cellular algorithms and architectures synthesis // Programmirovanie. – 1996. – № 4. – P. 24–36.

[7] Markova V. Cellular-pipelined algorithm architecture for polynomial computing // Lecture Notes in Computer Science. – Berlin: Springer-Verlag, 2001. – Iss. 2127. – P. 74–79.

[8] Medvedev Yu. Simulation of fluid and gas flows by cellular automata // Modeling of non-equilibrium system. Proceedings of the IV National Seminar (Krasnoyarsk, Oct. 12–14, 2001). – 2001. – P. 98 (in Russian).

[9] Nepomniaschaya A.S., Dvoskina M.A. A simple implementation of Dijkstra's shortest path algorithm on associative parallel processors // Fundamenta Informaticae. – Amsterdam: IOS Press, 2000. – Vol. 43. – P. 227–243.

[10] Nepomniaschaya A. Comparison of Prima-Dijkstra and Kruskal algorithms with the help of associative parallel processor // Kibernetica i systemny analiz. – 2000. – № 2. – P. 19–27 (in Russian).

[11] Piskunov S.V. Design of multilayer electrooptical structures // Avtometriya. – 1992. – № 4. – P. 14–27 (in Russian).

[12] Beletkov D.T., Ostapkevich M.B., Piskunov S.V., Zhileev I.V. WinALT, a software tool for fine-grain algorithms and structures synthesis and simulation // Lecture Notes in Computer Science. – Berlin: Springer. – 1999. – Iss. 1662. – P. 491–496.

[13] Piskunov S. Multilayer universal cellular structure and its electrooptical implementation // Avtometriya. – 1995. – № 3 (in Russian).

[14] Pudov S. Learning of cellular neural networks // Future Generation Computer Systems. – 2001. – Vol. 17. – P. 689–697.

[15] Pudov S.G. First-order cellular neural networks. Investigation and learning // Lecture Notes in Computer Science. – Berlin: Springer, 2001. – Iss. 2127. – P. 94–97.

[16] Selikhov A. Conditions of autowave process formation in cellular neural network // Sibirsky Zhurnal Vychislitelnoy Matematiki. – № 4. – P. 377–394 (in Russian).