European Science Foundation

Standing Committee for Physical and Engineering Science (PESC)

ESF PESC EXPLORATORY WORKSHOP

Cellular Computing (Complexity Aspects)

SCIENTIFIC REPORT

Research Group on Natural Computing
Sevilla University, Spain
January 30 – February 2, 2005

Convened by:
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Executive Summary

The ESF Exploratory Workshop "Cellular Computing (Complexity Aspects)" was held in Sevilla, Spain, in the organization of the Research Group on Natural Computing, Department of Computer Science and Artificial Intelligence, Sevilla University, from January 30 to February 2, 2005. January 30 was the day of arrivals, and the work of the meeting was scheduled for January 31 (Monday) – February 2 (Wednesday). The opening session was organized in "Salon de Grados" of the ETS de Ingenieria Informatica, while the presentations and the joint work was done in building L2, aula 1/4 of ETS Ingenieria Informatica, and the accommodation was organized in Hotel Al Andalus Palace (Avda. de la Palmera, s/n, Sevilla) and in the University Residence C.M. Hernando Colon (C. Sor Gregoria Santa Teresa, s/n, Sevilla). Besides the two convenors, the workshop has been attended by 28 invitees (Spain 5, Italy 5, England 3, Romania 3, Republic of Moldova 2, Hungary 2, The Netherlands 2, Austria 1, Poland 1, France 1, Finland 1), with other 17 participants (some of them attending only part of the works) being local researchers or being supported from other funds (Spain 9, Romania 3, Italy 3, India 1, Canada 1).

The goal of the workshop was to gather together a number of active researchers in membrane computing, in order to present recent results, to exchange ideas, and to cooperate on topics dealing with the (dynamic and static) complexity.

Membrane computing is a young branch of natural computing, aiming to abstract computing models from the structure and the functioning of the living cells, as well as from the co-operation of cells in tissues, organs, and organisms. The area has been initiated at the end of 1998, with the seminal paper first circulated on web and published in 2000 (Gh. Păun, Computing with membranes, *Journal of Computer and System Sciences*, 61, 1 (2000), 108–143; in 2003 ISI has considered the paper as "fast breaking", and the domain as "fast emerging area of computer science"). The basic computing models proposed in this framework (called P systems) are distributed parallel devices, processing multisets in the compartments defined by a cell-like hierarchy of membranes. The main ways of handling the multisets are by rewriting-like rules and by symport/antiport rules. Many ingredients inspired from biology or mathematically motivated were considered. Also tissue-like P systems and neural-like P systems were introduced. Most of the classes of P systems reported in the literature are able of universal computations, they can simulate Turing machines (both in the generative and the accepting modes). When possibilities of creating an exponential workspace in a linear time are provided, computationally hard problems (typically, NP-complete, but also PSPACE-complete problems) can be solved in a polynomial time. As ways to create space, mainly membrane division and membrane creation were used – both of them with a biological origin/motivation. In the last years, besides the theoretical (mathematical and computer science) investigations, the area of membrane computing proved to be an attractive framework for applications, especially in biology (modelling and simulating on computer various processes, mainly at the level of the cell), linguistics, management, computer science (computer graphics, devising approximate algorithms for solving hard optimization problems).

Details can be found in the dedicated web page at *http://psystems.disco.unimib.it*, organized in Milano, Italy, under the auspices of EMCC (European Molecular Computing Consortium).

In all these investigations, the complexity aspects are crucial – with the term "complexity" understood in the standard double sense: computational complexity (time and space necessary for solving a problem), descriptional complexity (initial size of P systems solving specific tasks) – with other related directions of research not yet explored in membrane computing: communication complexity (the cost of coordination/synchronization of computing agents), descriptive complexity (characterizing complexity classes in terms of logics).

Also the workshop was mainly devoted to presentations (and joint work) related to the first two areas, of dynamic complexity and static complexity. Among the topics dealt with in the presentations, we mention: formal aspects related to membrane computing complexity classes; relationships with classic complexity classes, especially with NP and PSPACE; a time–space combined complexity measure, specific to P systems (the so-called "Sevilla carpet"); considering the time of a computation not as a complexity measure, but as the result itself of the computation (related to, but not the same as time-constructible functions); the power of symport/antiport rules, compared with the power of Turing machines and restrictions of them; solving NP-complete problems by means of P systems with symport/antiport rules; solving parameterized NP-complete problems by means of P systems; links with quantum computing, with the possibility of devising efficient algorithms putting together ingredients both from quantum computing and membrane computing; solving Subset-sum in linear time by P systems with membrane creation; adapting Gandy's principles to membrane computing, thus getting a Turing bound on the computing power of P systems; efficient implementations of P systems, making use of parallelization or distributed hardware; links with grammar systems and eco-grammar systems; population P systems and relationships with quorum sensing in bacteria; the question of encoding the problems to solve via P systems, the possibility to have a standard binary encoding, although the multisets are unary data structures, etc.

Besides reporting recent results, the talks were on purpose oriented (by a pre-workshop interaction by internet and by the way the sessions were chaired) to research topics, to pointing ideas and proposals to be debated/continued, and in this way the interaction during the workshop was really high, with many new results obtained during the stay in Sevilla and, mainly, with a series of collaborations which will continue in the near future. Here are a few topics which were considered in joint works started during the workshop: possibilities of decreasing the height of Sevilla carpets; characterizations of Sevilla carpets in terms of growth functions of D0L systems; universality of P systems with active membranes without polarizations; uniform versus semi-uniform complexity classes; universality of symport/antiport P systems with a small number of membranes, a small number of objects, a small weight; solving 3-SAT in polynomial time with respect to the size of the input (in binary encoding and in a uniform way); measures of the non-determinism; possibilities of formalizing membrane operations from Cardelli's brane calculus in terms of P systems, etc.

Although most of participants were (young) computer scientists and mathematicians – with one biologist being invited, too – the workshop was highly interdisciplinary (many participants have solid biological knowledge, while both practical and theoretic aspects of computer science were considered).

As an overall estimation, membrane computing is perceived as a still fast growing area, with two central directions of research: complexity aspects (both static and dynamic), and applications (with a special interest for biology-medicine, and computer science). For sure,

the workshop has essentially contributed to the progress of the field, to its visibility, to the better integration of European groups working in this area.

The papers presented at the workshop, improved according to the discussions and enlarged with new results obtained during the meeting, will be collected in a volume, to be published in a couple of months with a publisher from Sevilla. A selection of additionally refereed papers will be considered for a special issue of *International Journal of Foundations of Computer Science*.

Scientific Content of the Event

The scientific programme consisted of presentation sessions and joint work sessions scheduled along the three working days of the workshop.

The opening welcome was given by professors M.J. Pérez-Jiménez (the head of the Research Group on Natural Computing from Sevilla University), Delia Balbontin-Noval (the director of the Department of Computer Science and AI from Sevilla University), and Gh. Păun (Ramon y Cajal researcher in Sevilla University, the "father" of membrane computing). After that, dr Fernando Sancho-Caparrini has presented ESF, using slides provided by the Foundation. The first presentation, by Gh. Păun, was both a general introduction to the workshop, with a brief glimpse to computational, descriptional, descriptive, communication complexity directions of research, and a challenge to address two research topics from a list of 26 topics the speaker has circulated on web before the meeting; one of these topics deals with the possibility to consider as the output of a computation the length of the computation, an idea which seems fruitful in membrane computing (and which started to be investigated together with R. Freund and M. Cavaliere). The second presentation was also of an introductory/general type; it was delivered by M.J. Pérez-Jiménez, and, besides basic concepts related to computational complexity in membrane computing, including complexity classes, it has proposed 10 open problems and research topics of interest for the area (some of them – uniform versus semi-uniform constructions of P systems, the use of polarizations, binary encoding of inputs – were already addressed during the workshop). Next, R. Freund has presented the state-of-the-art (at that moment, because during the meeting, in collaboration with A. Alhazov, Y. Rogozhin, S. Verlan, he has improved some of the results) concerning the universality results for systems with symport/antiport rules and a small number of membranes or of objects. Several tables containing the best known results were displayed – and improved during the workshop –, for instance, considering the number of membranes versus the size of rules, the number of membranes versus the number of objects, the number of membranes versus the number of rules; all these tables indicate a tighter and tighter borderline between universality and non-universality in the descriptional complexity of the mentioned class of P systems. The next talk, delivered by F.J. Romero-Campero, came back to dynamic complexity, addressing for the first time in membrane computing the possibility of solving parameterized problems (here, the Subset-Sum) by means of P systems – when membrane division or membrane creation are allowed, polynomial solutions can be obtained. Immediately after the lunch, A. Riscos-Núñez has presented his joint paper with M.A. Gutiérrez-Naranjo about the Sevilla carpet; besides basic concepts and illustrative examples, he proposed a series of parameters for assessing the complexity of a computation, all of them related to the Sevilla carpet. The problem was formulated during the discussions

to have trade-off theorems for parameters involved in the carpet: height, weight, width, etc., and the challenge was considered by various participants (G. Ciobanu, A. Alhazov, S. Verlan, M. Muskulus), who presented several ideas (mainly in the last day, during the panel discussion). It has followed a very provocative presentation by F. Bernardini, M. Gheorghe, N. Krasnogor, all of them delivering some part of the talk, about population P systems (cells placed in a common environment, establishing and cutting connections between them in a dynamic manner, with the aim of computing and, more interesting, to model tissues of cells or populations of bacteria), both with theoretical new ideas and with the intriguing new bio-inspired topic of quorum sensing known from experiments concerning the communication in populations of bacteria. The last presentation of the day was delivered by A. Alhazov (a PhD student working on a thesis in membrane computing, one of the most active participants in the workshop), who has presented a solution to an open problem circulating in the area: SAT can be solved in polynomial time by P systems with symport/antiport provided with membrane division rules (the result was known for tissue-like P systems, but not for cell-like P systems). After this presentation, about four hours most of the participants have continued to stay in the lecture room and in the neighboring seminar rooms and worked together until the closing of the university building.

The second day was opened by a presentation of the Milano team (the talk was given by A. Leporati), about quantum P systems; the main point was the possibility to use the quantum superposition in order to address in this framework various hard problems (as a possible contribution to the fact that in quantum computing there are at this moment only two types of algorithms, Shor and Grover, both of them not dealing with NP-complete problems). With biological motivations, D. Besozzi presented some proposals for defining fuzzy P systems, able to deal with imprecise estimations of the multisets present in a P system. This direction of research, although very important from the point of view of the collaboration with biologists, does not seem to raise a high interest among computer scientists, who use Gillespie-like approaches in practical applications (stochastic or probabilistic simulations). M.A. Gutiérrez-Naranjo has continued by presenting a way to solve Subset-sum problem, known to be NP-complete, in polynomial time by means of P systems with membrane creation; one of the novel ideas of his approach was to input the instance of the problem by means of a set of rules, not by means of a multiset of objects, as usual in membrane computing when attacking NP-complete problems. Next talk, again with a presentation done by both authors, M. Cavaliere and V. Deufemia, dealt with the possibility to apply membrane computing in modelling a real-life situation (the itinerary of a patient in a hospital), and has addressed several problems similar to those encountered in software engineering (e.g., program checking, filtering the information through a suitable observer in such a way to get a decidable set of trajectories, if possible without loosing too much information). During discussions, this approach was put in relation both with the applications of membrane computing in management issues and with program checking, where similar techniques are already known and might be adapted to the P systems case. The following talk, by D. Sburlan (the paper is written together with M. Cavaliere) dealt with a very important and sensitive issue in membrane computing: using or not an universal clock, the role of time, of synchronization. The authors have proposed two ways to relax the strong assumption of having a global clock: time-free and clock-free systems. In the first case, the rules have a duration which is either known in advance or is dynamically computed, depending on the

multiset where they are applied, in the second case the time is not known; in both cases, one investigates the effect of this assumption on the computing power of systems (with interesting results stating that in certain cases the time does not matter, the systems have the same power with or without a clock, while in other cases the opposite result holds). A very provocative issue was considered by A. Obtulowicz in his talk about Gandy's principles for computing mechanisms (in the framework of the four general principles formulated by R. Gandy already in 1980 one can prove that a computing model cannot overpass Turing barrier of computability); the main problem addressed by the speaker was the formulation of these principles in terms of membrane computing; without completing the task, the speaker made significant steps towards it, by formalizing the notion of a hereditary set in terms of P systems. The next talk, by G. Vaszil, was devoted to an important class of P systems, those working in the accepting mode, also called P automata; these systems accept sequences of multisets, which can be arbitrarily large, hence the problem of working with infinite alphabets arises (the author has linked the case of P automata to classic approaches in automata theory to infinite alphabets, such as F. Otto's one). The next two talks came from G. Ciobanu's team in Timisoara, Romania, and both of them were devoted to implementations of P systems. The first talk (joint work with D. Petcu) was received enthusiastically: making use of the intrinsic parallel character of P systems, the parallelization proposed in the talk and effectively implemented showed an impressive efficiency, sometimes close to hundred percents. This approach was immediately put in connection with Nishida's membrane algorithms for solving optimization problems; because those algorithms are essentially distributed, their parallelization can lead to important speed-ups, which is of a clear interest when dealing with practical problems. The other talk (joint work of G. Ciobanu with C. Izbasa, C. Bonchis, C. Garboni) has described a CLIPS implementation of P systems with multisets processed by rewriting-like rules; besides the efficiency of the core engine of the program, the interfaces of the program were discussed, e.g., the possibility to synthesize the information in the form of a Sevilla carpet, or to make the program easy to use by a biologist. Again, the afternoon was devoted to joint work, with the mentioning that this time the work had to stop earlier: it was the evening of the workshop special dinner.

The last day of the workshop was shorter in presentations, only the morning was devoted to formal talks, while the afternoon was dedicated to joint work, and to informal discussion related to results obtained during the meeting. The first presentation, by E. Csuhaj-Varju, dealt with the connection between P systems and grammar systems, with the focus on a variant of P systems resembling the so-called eco-grammar systems, a grammatical model proposed a decade ago in the framework of artificial life. The EP-colonies proposed by the speaker are rather complex models, extending the P colonies defined recently by E. Csuhaj-Varju and several collaborators of her; the key point is the interaction of the "computing agents" with the environment, an issue important both in biology and in modern computer science and easy to capture in membrane computing. The talk by C. Zandron was devoted to the possibility of encoding the input in a P system which solves a computationally hard problem in a binary form, as standard in complexity theory, and not in a unary form, as usual in membrane computing, because of the restriction of using multisets (hence data structures essentially unary in nature). The idea proposed by the speaker, developed further during the workshop in cooperation with other participants (A. Leporati, M.J. Pérez-Jiménez) seems

to work in the semi-uniform framework, thus bringing the membrane computing complexity classes closer to the standards of complexity theory. The last formal talk of the workshop was delivered by S. Verlan, who discussed splicing P systems with only one membrane, with a subtle distinctions between five modes of handling copies of strings present in a compartment; for four of these possibilities, he has presented computability power results (universality in three cases), with the fifth case remaining open.

The panel discussion which has ended the meeting was devoted mainly to concluding remarks (by Gh. Păun, M.J. Pérez-Jimenez, M. Gheorghe, etc.) and to short presentations of results obtained during the workshop, especially meant to point to problems discussed before and solved, so that no further efforts should be devoted to them. The speakers were A. Alhazov, M. Muskulus, M.J. Pérez-Jiménez, R. Freund, and M.A. Gutiérrez-Naranjo.

Assessment of the Results, Contribution to the Future Direction of the Field

As expected, the workshop was very fruitful, with the flexible organization (explicit time for discussion and for joint work provided in the programme) proving its full efficiency. The meeting was prepared by an active internet communication, including a list of open problems and research topics circulated in advance, so that the interaction during the meeting was impressive. Not only the number of questions and comments during the presentations was very high, but also the cooperation in teams formed after the formal talks and addressing issues formulated during the presentations was great, with many hours of joint work in the afternoons, in many cases with blackboard interaction.

The results presented gave a good overview of the state-of-the-art of complexity investigations in membrane computing, with a large panoply of open problems and research topics made explicit, in many cases with a better formulation as the authors had before the meeting.

The main indication of success, besides the active discussion and cooperations, is the number of results obtained during the meeting, to be materialized in the papers which will be collected in the proceedings volume. We expect a volume of about 300 pages, with many papers started during the workshop, and with almost all participants involved as (co)authors.

At a technical level, the workshop has stressed several directions of research concerning the complexity aspects of cellular/membrane computing:

1. The area is already mature enough to address difficult problems, such as characterizations of classic complexity classes in terms of membrane computing complexity classes, or the characterization of the P = NP problem; furthermore, subtle issues can now be considered, such as the necessity of using polarizations, the difference between uniform and semi-uniform, deterministic and confluent approaches when solving NP-complete problems, etc.

2. Although the descriptional complexity was much investigated, many interesting and challenging problems are still open (example: the power of P systems with a very reduced size), while new problems appear (considering new complexity parameters, such as the number of evolution rules).

3. The combined time-space approach, through Sevilla carpet, deserves a further research, as several interesting issues can be formulated in this framework (combined complexity, fairness, degree of trade-off).

As concrete results of the workshop, we mention:

1. A better coordination of European groups working in membrane computing.
2. The training of many y oung people, PhD students included, in conducting research, cooperating, presenting the results of their work.
3. Several papers which will be published both in the workshop volume and, in a revised form, submitted to journals and conferences, thus bringing visibility to the domain and the event.

Final Programme

Monday, January 31

9.00 – 10.00:	Registration
10.00 – 10.10:	Opening
10.10 – 10.30:	Presentation of ESF
10.30 – 10.50:	Gh. Păun: Complexity aspects of membrane computing: Some further open problems
10.50 – 11.00:	Discussions
11.00 – 11.30:	Coffee break
11.30 – 11.50:	M.J. Pérez-Jiménez: Computational complexity aspects of membrane computing: Ideas, results, open problems
11.50 – 12.00:	Discussions
12.00 – 12.20:	R. Freund: P systems with symport/antiport: current universality results
12.20 – 12.30:	Discussions
12.30 – 12.50:	M.L. Pérez-Jiménez, F.J. Romero-Campero: Solving parameterized NP-complete problems by means of P systems
12.50 – 13.00:	Discussions
13.00 – 15.00:	Lunch
15.00 – 15.20:	M.A. Gutiérrez-Naranjo, A. Riscos-Núñez: On time-space complexity of P systems: Sevilla carpet
15.20 – 15.30:	Discussions
15.30 – 15.50:	F. Bernardini, M. Gheorghe, N. Krasnogor: Complexity aspects in population and quored P systems
15.50 – 16.00:	Discussions
16.00 – 16.20:	A. Alhazov: Solving SAT in polynomial time by means of cell-like P systems with symport/antiport
16.20 – 16.30:	Discussions
16.30 – 17.00:	Coffee break
17.00 – 20.00:	Joint work

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Tuesday, February 1

9.00 – 9.20:	A. Leporati, G. Mauri, Cl. Zandron: Quantum P systems
9.20 – 9.30:	Discussions
9.30 – 9.50:	D. Besozzi, C. Manara: Fuzzy P systems
9.50 – 10.00:	Discussions
10.00 – 10.20:	M.A. Gutiérrez-Naranjo: Membrane creation with input rules (solving Subset-Sum in linear time)
10.20 – 10.30:	Discussions
10.30 – 10.50:	V. Deufemia, M. Cavaliere: Specifying dynamic software architecture by using membrane systems
10.50 – 11.00:	Discussions
11.00 – 11.30:	Coffee break
11.30 – 11.50:	M. Cavaliere, D. Sburlan: Time-independent P systems
11.50 – 12.00:	Discussions
12.00 – 12.20:	A. Obtulowicz: Gandy's principles for mechanisms and membrane computing
12.20 – 12.30:	Discussions
12.30 – 12.50:	G. Vaszil: Complexity problems about P automata over infinite input alphabets
12.50 – 13.00:	Discussions
13.00 – 15.00:	Lunch
15.00 – 15.20:	G. Ciobanu, D. Petcu: P Accelerators: Parallelization of sequential simulators
15.20 – 15.30:	Discussions
15.30 – 15.50:	C. Izbasa, C. Bonchis, C. Garboni, G. Ciobanu: WebPS: a web-enabled P system simulator with query facilities
15.50 – 16.00:	Discussions
16.00 – 16.30:	Coffee break
16.30 – 20.00:	Joint work
20.30 – ??.00:	Workshop special dinner

Wednesday, February 2

9.00 – 9.20:	E. Csuhaj-Varjú: Membrane systems versus grammar systems; EP-colonies
9.20 – 9.30:	Discussions
9.30 – 9.50:	C. Zandron: Unary versus binary encodings in solving NP-complete problems
9.50 – 10.00:	Discussions
10.00 – 10.20:	S. Verlan: The power of one membrane
10.20 – 10.30:	Discussions
10.30 – 11.00:	Coffee break
11.00 – 13.00:	Panel-brainstorming: Complexity in cellular (membrane) computing
13.00 – 15.00:	Lunch
15.00 – 17.55:	Joint work
17.55 – 18.00:	Closing

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Statistical Information on Participants

A. Country of origin:

	Invited participants	Other participants
Austria	1	–
Canada	–	1
England	3	–
Finland	1	–
France	1	–
Hungary	2	–
India	–	1
Italy	5	3
Poland	1	–
Republic of Moldova	2	–
Romania	3	3
Spain	5	9
The Netherlands	2	–
Convenors	2	–
Total	28	17

B. Age structure:

	20 – 30 years	30 – 40 years	40 – 50 years	over 50 years
Invited	9 participants	5 participants	6 participants	8 participants
Others	11 participants	4 participants	–	2 participants

C. PhD status:

	PhD student	Recent PhD	PhD since at least 5 years
Invited	6 participants	7 participants	15 participants
Others	9 participants	6 participants	2 participants