Selected Scientific Achievements from DIMACS Special Foci

Every one of DIMACS' special years and special focus programs has led to major scientific breakthroughs, stimulated new directions of research expected to continue for years to come, and forged lasting new partnerships among diverse scientific communities. The results are often unexpected and have been obtained by bringing together outstanding scientists, involving first-rate junior people, running a focused series of workshops and working group meetings, and providing opportunities for intensive interaction, often between individuals from different fields of the mathematical/computational sciences or from different disciplines. DIMACS special foci have been evaluated by committees of experts and their reports may be viewed at http://dimacs.rutgers.edu/About/index.html#reports. All give high praise to the special foci, trace their dramatic impact on the development of a field, on the creation of new partnerships and collaborations, and on the careers of those involved, and include many citations of papers directly traceable to the special year, many of them seminal.

In describing a few of the many results traceable to DIMACS special years/foci, we use the abbreviations PM for permanent member, V for visitor, and PD for DIMACS postdoc.

The first DIMACS Special Year, on Discrete and Computational Geometry, run in 1989-90, led to the solution of several major open problems. Ding-zu Du (PD) and Frank Hwang (then PM) proved the 22-year-old Gilbert-Pollak conjecture that the minimum ratio between the length of a Steiner minimum tree and a minimum spanning tree is $\sqrt{3}/2$. This led to improved heuristics for the design of more efficient communication networks. Also, Bernard Chazelle (PM) solved the longstanding open problem of finding a linear-time algorithm for triangulating a simple polygon (without adding new vertices). The work of Jiri Matousek (V) on derandomizing epsilon-net constructions and computing hyperplane cuttings has been very influential and led Chazelle to derive the first optimal deterministic convex hull algorithm, solving one of the most central problems in computational geometry.

DIMACS' Special Year on Complexity Theory of Interactive Computing played a central role in one of the most important developments in theoretical computer science in recent years, the development of ways to reformulate computer "proofs" so that the correctness of a computation can be verified with arbitrarily high confidence by a small number of random spot checks. A critical result leading to these developments, the discovery of connections between interactive proofs and approximation algorithms, was a direct result of the Special Year. It arose from the interactions between two diverse communities, the cryptography community and the combinatorial optimization community, and came about by applying recent methods of cryptography to the maximum clique problem of combinatorial optimization. The key results were obtained by Uriel Feige (PD), Shafi Goldwasser (V), Laszlo Lovász (then PM), Shmuel Safra (V), and Mario Szegedy (V).

One of the most famous open problems in graph theory is the Hadwiger conjecture, which states that every graph not contractible to the complete graph on $k+1$ vertices is colorable in k colors. As an outgrowth of the Special Year on Graph Theory and Algorithms, Neil Robertson (V), Paul Seymour (PM), and Robin Thomas (V) proved the case $k = 5$ of this conjecture. (The case $k = 4$ is equivalent to the four color conjecture.) Later, they and Dan Sanders (V), in work also heavily influenced by this Special Year, obtained a much improved proof of the four color theorem. The new proof still relies on a computer, but is simpler in its details and more accessible to complete checking than the original proof, and has been modified to obtain important results about cubic graphs that are almost planar.

During the Special Year on Graph Theory and Algorithms, a group of researchers from four different institutions, PM's David Applegate, Vasek Chvatal, and Bill Cook, together with Bob Bixby (V), collaborated to solve what at that time was the "world's largest" unsolved Traveling Salesman Problem. The TSP problem they solved arose from the question of how to most efficiently connect 3,038 points for drilling holes in making a circuit board.

Through the Special Year on Mathematical Support for Molecular Biology, the most dramatic developments were the real collaborations between biological scientists and mathematicians/computer scientists. For example, computer scientist Dannie Durand (then PM), a participant in the Special Year postdoctoral program, and Lee Silver of the Princeton Molecular Biology Department, who met through the Special Year tutorial, overturned a 40-year-old hypothesis in biology about ultraselfish genes in mice. (The hypothesis was that the low level persistence of the t-haplotype in natural populations is due to a balance between loss of the gene due to stochastic effects in small populations and reintroduction of the gene through migration.) Also during this Special Year, an "algorithm implementation challenge" on "shotgun sequencing" led to the discovery by biotech companies that right.

In many complex systems underlying modern society, small faults in hardware or software can cause system failures with severe consequences, as for example occurred with the $474M Pentium chip division bug and the $5B crash of the Ariane 5 rocket. The field of computer-aided verification (CAV), concerned with use of appropriate formal methods to judge program correctness, has grown enormously since a 1990 DIMACS CAV workshop that sparked development of the field, and is vitally important in the work of a myraid of major companies. Logic has become an important tool for CAV, in particular temporal logic, a language for expressing relationships between events occurring over time. During the Special Year on Logic and Algorithms, as a dramatic result of DIMACS' efforts to bring together two distinct research communities, ideas from finite model theory were used to solve a problem of computer-aided verification concerning the expressibility of temporal logic statements. Kousha Etessami (PD), Denis Therien (V), and Thomas Wilke (PD) designed a new Ehrenfeucht-Fraisse game to capture the power of temporal logic. This in turn led to a collaboration between two computer scientists and a logician, F. Gradel (V), P. Kolaitis (V), and Moshe Vardi (V), to solve a classical open problem by proving that the decision problem for first-order logic with two variables is NEXPTIME-complete. The collaboration between Etessami and Wilke that sparked these developments would almost certainly not have happened if not for DIMACS and its Special Year tutorial. They would likely not have ever spoken to each other, because they were part of different communities.

Two research projects resulted from the Special Year on Massively Parallel Computing. The projects developed the first model and simulation of the global Internet with a hundred thousand hosts and routers, running IP packets with real routing protocols at a rate of more than one million packet hops per second. The resulting software is now used by opver 40 companies and university research teams.

During the Special Year on Networks, Joe Kilian (PM) and Erez Petrank (PD) developed an escrowed identity system to protect privacy in electronic toll collection and related applications. In the first tier of this 2-tiered system, enough information is provided by the user so that an operator can be sure the user is legitimate, but otherwise the user's identity is protected. If more information is required, for example in the case of a crime, the second tier provides it, through involvement of a third party (an escrow agent).

In bin packing applications, such as in packing small information sets into larger, fixed-size ones, we can think of a random process generating items of various sizes to be packed into fixed-size bins. Standard bin packing algorithms such as Best Fit do not typically perform optimally. This is true even for offline algorithms such as Best Fit Decreasing. During the special year on Large Scale Discrete Optimization, Janos Csirik (V), David Johnson (PM), Claire Kenyon, Peter Shor (PM), and Richard Weber developed a new and remarkably simple on-line bin packing algorithm that performs optimally (in an average case sense) for all discrete distributions of item sizes.

In DNA computing, the goal is to use biological processes undergone by DNA and other biomolecular sequences to perform useful and difficult computations. During the special focus on DNA computing, Biologist Laura Landweber (PM) and computer scientist Richard Lipton (PM) collaborated in work that rapidly progressed from the theory to the wet lab. In an important breakthrough, Landweber, Lipton, and their colleagues designed a computer built from RNA to solve a chess problem, the problem of determining the positions knights can occupy on a chessboard such that no knight can attack any other knight on the board. Though not NP-complete for a defined board, this problem is from the class of NP-complete "satisfiability" problems. Anthony Cukras, Dirk Faulhammer, Lipton, and Landweber developed a theory of RNA computing and a method for solving the knight problem. Using only biological molecules and enzymes as tools, they developed and successfully executed an algorithm for solving this variant of the knight problem on a 3x3 chessboard using a 10-bit combinatorial pool and a protocol involving sequential R-NASE H 'destroy' operations. The results of preliminary experiments revealed that the protocol recovers far more correct solutions than expected at random, and further work led to the successful completion of the largest molecular computation in any lab to that time.

There has long been interest in using computers to mimic the process of scientific discovery. A more recent effort has been to use computers to actually generate new scientific conjectures which are then explored by researchers. As part of the special focus on Data Analysis and Mining, a working group explored the use of computers to generate such conjectures, with emphasis on conjectures in graph theory and chemistry. At its first meeting, this group explored conjectures generated by various software systems and Dragan Stevanovic (V) then proved a well-known conjecture generated by the software system Graffiti. Fullerenes are molecular graphs corresoponding to carbon isomers. From the graph-theoretical point of view, they are planar 3-regular graphs having either pentagons or hexagons for their faces. The conjecture proved was that the "separator" of a fullerene is at most 1. Using the interactive component of another computer-generating software system, AGX, Stevanovic and Gilles Caporossi (V) simplified the proof to show that the dodecahedron has the largest separator among all fullerenes.

The general belief in statistical physics is that spontaneous symmetry-breaking is something that, if it occurs at all, occurs when the temperature drops below some unique critical point. This had indeed been proved for the Ising model. During the special year on Discrete Probability, a partnership among discrete mathematicians, computer scientists, and statistical physicists led to the solution to the long-open question of whether the same thing holds for the Widom-Rowlinson model, which is to the Ising exactly as vertices are to edges of a graph. Graham Brightwell (V), Olle Haggstrom (V), and Peter Winkler (PM) settled this in the negative by constructing a non-regular tree in which, as temperature is lowered, symmetry is broken, then re-established, then broken again.