Research Statement

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Current Research

My current research focuses on several algorithmic problems which are considered to be important in computational geometry. Most of the problems I am interested in are related to Voronoi diagrams, geometric shortest paths, geometric networks, geometric optimization, and their applications to other fields.

Shortest Paths in Polygonal Domains and Related Problems

A *polygonal domain* P is a connected region bounded by a polygon with holes. More specifically, it consists of an outer polygon and a number h of holes inside the outer polygon. Any feasible path should stay inside P and the shortest path between any two points inside P minimizes its length among all feasible paths connecting the two points. Since such shortest paths are defined between any pair of points in P, their lengths naturally induce a metric d on P, called the geodesic distance.

The polygonal domain is one of the most favorite topics in computational geometry. One of the major interests in computational geometry in the 1980s and 1990s was to extend geometric knowledge of the classical Euclidean metric to the geodesic distance in a polygon P *without holes*. It was fairly successful with lots of interesting observations and efficient algorithms. However, it seems much more difficult to attack problems when P assumes holes. My recent research focuses on extending results without holes to those with holes.

- Given a set S of k points (called sites), the *geodesic farthest Voronoi diagram* is a partition of P into cells in which each point has a common farthest site among S with respect to the geodesic distance. If P has no hole ($h = 0$), it is known in 1989 that the diagram has $O(n + k)$ complexity and can be computed in $O((n + k) \log(n + k))$ time. Here, n denotes the complexity of P. One of my recent work was to extend this result to polygonal domains with holes. At last, I obtained the following result: the complexity of the geodesic farthest Voronoi diagram is $\Theta(nk)$ in the worst case for any $h \geq 1$ and can be computed in $O(nk \log^3(n + k))$ time. There was no known nontrivial upper bound or algorithm for last 20 years. This result has been presented at the 25th ACM Symposium on Computational Geometry (SoCG 2009), which is considered as a best conference not only in computational geometry but also in the whole theoretical computer science.

- The *two-point shortest path query problem* is to build an efficient structure that processes the following query in sublinear time or even $O(\log n)$ time: find a shortest path between a given pair of two points in P. Without any such structure, computing a shortest path between a given pair of points can be done in $O(n \log n)$ time. Also, if $h = 0$, an optimal structure of size $O(n)$ with $O(\log n)$ query time has been presented in 1989. Assuming holes, Chiang and Mitchell (1999) presented several such structures that serve sublinear query time. Their structures, however, require significantly large storage; $O(n^{11})$ space for $O(\log n)$ time query and $O(n^{5+\epsilon})$ for sublinear $o(n)$ time query.

  In May of 2009, I visited Dr. Yoshio Okamoto, an associate professor in Tokyo Institute of Technology, and introduced a variation of this problem where the query points are restricted on a specified subset of P. We worked on it together and made some progress, obtaining query structures of much less storage with the same query time. The results got accepted for presentation at the 20th International Symposium on Algorithms and Computation (ISAAC 2009), which is a top-class conference on algorithms and will be held in December 2009.

- The *geodesic diameter* problem is to find a farthest pair of points in P with respect to the geodesic distance. If there is no hole inside P, this problem can be solved surprisingly in $O(n)$ time. On the other hand, more surprisingly, there is no known algorithm when P has holes. This is an old problem but nobody has succeeded in obtaining an algorithm for last two decades. I am working on this problem also with colleagues, and we have obtained a first polynomial time algorithm based on several new observations. We are planning to continue working on this problem, finding more efficient algorithms and the hardness of the problem, and finally to submit the results to a top conference and journal in theoretical computer science.

Geometric Transportation Networks and Travel Time Metrics

This is the subject considered in my Dissertation. Motivated by the real-world transportation networks, I introduced a mathematical model of transportation networks embedded on the plane and defined travel time metrics induced by a given transportation network and an underlying metric. The travel time metric evaluates the minimum possible elapsed time during travel from a point to another on the plane.

In the dissertation, I presented several efficient algorithms for fundamental problems under the travel time metric, which include finding a shortest travel time path, computing the Voronoi diagram or the farthest Voronoi diagram, and searching an optimal location where a new network is constructed. The work done in the dissertation has been presented many times at international conferences on algorithms (with at least 5 conference papers, except domestic ones) and published as at least three journal articles. Recently, another result has been presented at Workshop on Algorithms and Computation (Feb. 2009) in cooperation with Prof. Takeshi Tokuyama and his student Matias Korman when I visited his laboratory in Tohoku University.

However, there are still several open issues:

- Still many algorithms for computing *Voronoi diagram under the trave time metric* are not optimal in their time complexity. Part of my future work will be continuation of this topic to find more efficient and finally optimal algorithms.

- Part of my dissertation is devoted to a problem of finding *optimal location of transportation networks* of simple shape such as a line or a pair of lines. This work was done in cooperation with 9 colleagues over the world. This geometric location problem, together with our results, has been focused by other researchers and several extended results were recently presented. However, the currently best results also deal with very simple cases, like a single line segment. Lots of variations and extensions on this problem still remain open. As a long-term research, I plan to attack such extensions of this problem gradually, publishing achieved results periodically.

- *Dynamic transportation networks* would be a next challenging target. The real-world transportation network is in fact *not static*: Imagine a modern, crowded city where you live. Street conditions are often changed as time flows; for instance, we suffer daily rush hour and some streets or roads could be blocked by an accident while a new shortcut could be open over last night. Dynamic transportation networks reflect such traffic condition that dynamically changes. In this situation one would ask to efficiently report a shortest (travel time) path between a user-queried pair of two points. This sort of dynamic shortest path has been researched only on graphs but the proposed model expands our space to a whole plane.

Covering Points with Rectangles

This is a geometric optimization problem, which is typical, fundamental, and thus important. Given a set of n points in the plane and a positive integer k, the problem is to find an optimal set of k rectangles whose union contains all the n given points. Here, the optimality is specified by various objective functions on the set of rectangles; for example, the maximum area or perimeter, or the sum of the areas of the rectangles. Also, the possible set of covering rectangles may be restricted in several ways; for example, pairwise disjointness, bounded aspect ratio, and so on. If rectangles are replace by squares, then the problem of minimizing the maximum area or perimeter is exactly identical to the well-known *rectilinear k-center* problem, which is known to be NP-hard. The rectilinear k-center problem has taken constant interests from computational geometry community, resulting in hardness results mentioned above and several approximation algorithms.

However, there are few partial results for the rectangle cases. Indeed, it is believed that the rectangle case would be more difficult than the square cases since a rectangle has one more degree of freedom. Known results on this problem consider the case for small k, mostly $k \leq 3$, and no NP-hardness proof is known so far. I have been working on this problem mostly with Dr. Hee-Kap Ahn, an assistant professor in POSTECH, and publishing a couple of papers. Recently, we obtained a NP-hardness proof of a variation of the problem. This work is still in progress with members of Geometric Computing Lab. in POSTECH. I think the technique of our proof can be applied to many other variations. We have presented some partial results at an international conference, called FAW 2009 (Jun. 2009), and will soon submit a journal article (expected in October 2009).

Steiner Tree Problems and Applications to Wireless Sensor Networks

Finding application domains of geometric knowledge is another focus of my research, and this problem is one of the cases. While working as a postdoctoral researcher at KAIST, I found that *coverage problems in wireless sensor networks* intensively exploit geometric structures which are well understood in computational geometry. In coverage problems, mainly considered are how to evaluate the given network under a specified measure for coverage and how to deploy more sensors to improve the coverage measure the most. In cooperation with Dr. Sunghee Choi (KAIST) and her students, I obtained some new and improved results on those problems with interesting connection with some geometric structures, called the *bottleneck Steiner trees*. The bottleneck Steiner tree problem has been studied in Operations Research community in the 1990s. For this problem, we tried to obtain efficient exact algorithms. As a result, we have published one conference paper at WALCOM 2009 (Feb. 2009) and will present one another at ISAAC 2009 (Dec. 2009). We also applied these new algorithms to coverage problem in wireless censor networks and achieved very nice experimental results compared with previous known methods. This result has been submitted to IEEE INFOCOM 2010; the notification of acceptance is scheduled to be out in November, 2009.

In addition, I continue to seek other problems where I have advantage with more geometric knowledge. When I was a PhD candidate, I had a good experience; in problem of extracting the domain-domain interaction surface between two protein molecules, I was able to help bioinformatics researchers by a simple algorithm using Voronoi diagrams in space.

Research Agenda

I plan to put my priority on polygonal domains and related problems for at least one or two years. Expected results on the problems by myself and my colleagues would have fairly strong impact in computational geometry and some related application domains, and we are in the state of making positive progress. We will soon be able to start publishing a series of papers on the problems.

The rectangle covering problem is another important class of optimization problems. Due to recent progress on this problem in cooperation with Dr. Ahn and his group, nowadays I focus mostly on the rectangle covering. As mentioned above, only few results are known on this problem to the community. We thus expect that our research on this problem provide lots of interesting and impressive results.

The problems on transportation networks and travel time metrics are relatively less urgent. It seems not very challenging to improve the currently best algorithms, and I expect that several improved algorithms will be achieved in near future. On the other hand, the other two subjects seem more difficult: Finding an optimal transportation network of more complicated shape is conjectured to be NP-hard but nothing is known so far. The shortest travel time path on dynamic transportation networks would be another challenge. The shortest path problem on a dynamic graph, where edges are inserted or deleted one by one, is already proved to be hard. As a long-term research, I plan to attack these challenges gradually, publishing achieved results periodically.

In addition to the coverage problems in wireless sensor networks, I will continue part of my efforts on finding interesting applications of computational geometry in sensor networks, structural bioinformatics, computer graphics, and so on. This would be difficult just by myself; hints from experts in each domain are crucial. To achieve this goal, I try to communicate with researchers in various application domains.

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