

Voronoi Diagrams — A Survey of a Fundamental Geometric Data Structure

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This paper presents a survey of the Voronoi diagram, one of the most fundamental data structures in computational geometry. It demonstrates the importance and usefulness of the Voronoi diagram in a wide variety of fields inside and outside computer science and surveys the history of its development. The paper puts particular emphasis on the unified exposition of its mathematical and algorithmic properties. Finally, the paper provides the first comprehensive bibliography on Voronoi diagrams and related structures.

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INTRODUCTION

Computational geometry is concerned with the design and analysis of algorithms for geometrical problems. In addition, other more practically oriented, areas of computer science—such as computer graphics, computer-aided design, robotics, pattern recognition, and operations research—give rise to problems that inherently are geometrical. This is one reason computational geometry has attracted enormous research interest in the past decade and is a well-established area today. (For standard sources, we refer to the survey article by Lee and Preparata

[1984] and to the textbooks by Preparata and Shamos [1985] and Edelsbrunner [1987b].)

Readers familiar with the literature of computational geometry will have noticed, especially in the last few years, an increasing interest in a geometrical construct called the *Voronoi diagram*. This trend can also be observed in combinatorial geometry and in a considerable number of articles in natural science journals that address the Voronoi diagram under different names specific to the respective area. Given some number of points in the plane, their Voronoi diagram divides the plane according to the *nearest-neighbor*

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rule: Each point is associated with the region of the plane closest to it; (Figure 1).

Why do Voronoi diagrams receive so much attention? What is special about this easily defined and visualized construct? It seems three main reasons are responsible. First, Voronoi diagrams arise in nature in various situations. Indeed, several natural processes can be used to define particular classes of Voronoi diagrams. Human intuition is often guided by visual perception. If one sees an underlying structure, the whole situation may be understood at a higher level. Second, Voronoi diagrams have interesting and surprising mathematical properties; for instance, they are related to many well-known geometrical structures. This has led several authors to believe that the Voronoi diagram is one of the most fundamental constructs defined by a discrete set of points. Finally, Voronoi diagrams have proved to be a powerful tool in solving seemingly unrelated computational problems and therefore have increasingly attracted the attention of computer scientists in the last few years. Efficient and reasonably simple techniques have been

developed for the computer construction and representation of Voronoi diagrams.

The intention of this survey is threefold: First, motivated by the fact that Voronoi diagrams have been (re)invented and studied fairly independently in the applied natural sciences, in mathematics, and in computer science, it presents sketches of their historical development in these three areas. Second, it surveys the literature on Voronoi diagrams and related structures, with particular emphasis on the unified exposition of their mathematical and computational properties and their applications in computer science. Finally, it provides the first comprehensive bibliography on Voronoi diagrams.

Basic Properties of the Voronoi Diagram

We begin with a description of elementary, though important, properties of the Voronoi diagram that will suggest some feeling for this structure. We also introduce notation used throughout this paper. See also Preparata and Shamos [1985] or Edelsbrunner [1987] for sources on this material.

We first give a usual generic definition of the Voronoi diagram. Let S denote a set of n points (called *sites*) in the plane. For two distinct sites $p, q \in S$, the *dominance* of p over q is defined as the subset of the plane being at least as close to p as to q . Formally,

$$\text{dom}(p, q) = \{x \in R^2 \mid \delta(x, p) \leq \delta(x, q)\},$$

for δ denoting the euclidean distance function. Clearly, $\text{dom}(p, q)$ is a closed half plane bounded by the perpendicular bisector of p and q . This bisector separates all points of the plane closer to p from those closer to q and will be termed the *separator* of p and q . The *region* of a site $p \in S$ is the portion of the plane lying in all of the dominances of p over the remaining sites in S . Formally

$$\text{reg}(p) = \bigcap_{q \in S - \{p\}} \text{dom}(p, q).$$

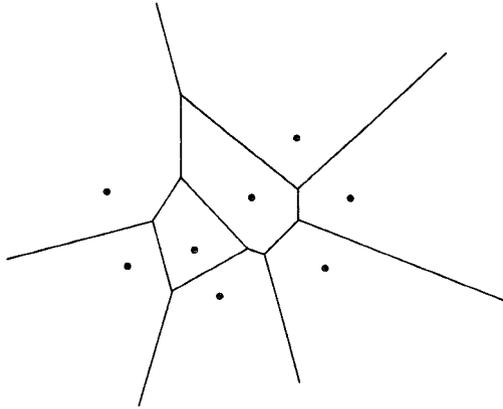


Figure 1. Voronoi diagram for eight sites in the plane.

Since the regions are coming from intersecting $n - 1$ half planes, they are convex polygons. Thus the boundary of a region consists of at most $n - 1$ edges (maximal open straight-line segments) and vertices (their endpoints). Each point on an edge is equidistant from exactly two sites, and each vertex is equidistant from at least three. As a consequence, the regions are edge to edge and vertex to vertex, that is to say, they form a polygonal partition of the plane. This partition is called the *Voronoi diagram*, $V(S)$, of the finite point-set S (Figure 1).

Note that a region, say $\text{reg}(p)$, cannot be empty since it contains all points of the plane at least as close to p as to any other sites in S . In particular, $p \in \text{reg}(p)$. It follows that $V(S)$ contains exactly n regions. Some of them are necessarily unbounded. They are defined by sites lying on the boundary of the convex hull of S because just for those sites there exist points arbitrarily far away but still closest.¹ No vertices occur if and only if all sites in S lie on a single straight line. Such degenerate configurations also imply the existence of regions with only one (unbounded) edge. Otherwise, three or more edges meet at a common vertex. It

¹The *convex hull* of S is the smallest convex polygon that contains S .

should be observed that each vertex is the center of a circle that passes through at least three sites but encloses no site.

Although n sites give rise to $\binom{n}{2} = O(n^2)$ separators, only linearly many separators contribute an edge to $V(S)$. This can be seen by viewing a Voronoi diagram as a planar graph with n regions and minimum vertex degree 3. Each of the e edges has two vertices, and each of the v vertices belongs to at least three edges. Hence, $2e \geq 3v$. Euler's relation $n + v - e \geq 2$ now implies $e \leq 3n - 6$ and $v \leq 2n - 4$. Thus, for example, the average number of edges of a region does not achieve six; there are less than $3n$ edges, and each of them belongs to exactly two of the n regions.

The linear behavior of the size of the Voronoi diagram in the plane means that, roughly speaking, this structure is not much more complex than the underlying configuration of sites. This is one of the main reasons for the frequent use of Voronoi diagrams. A second reason is that $V(S)$ comprises the entire proximity information about S in an explicit and computationally useful manner. For example, its applicability to the important post-office problem (see below) is based on the trivial observation that a point x falls into the region of a site p if and only if p is closest to x among all sites in S . Moreover, if site p is closest to site q , then $\text{reg}(p)$ and $\text{reg}(q)$ share a common edge. This particularly implies that the closest pair of sites in S gives rise to some edge of $V(S)$.

Applications in Computer Science

To substantiate the usefulness of the Voronoi diagram in computer science, we briefly describe four situations where this structure is used. The practicality and diversity of these applications will impart the appeal of Voronoi diagrams.

Associative File Searching

Consider some file of n two-attribute records referring, for example, to latitude and longitude of a city or to age and

income of a person. Suppose we are given an additional target record R and we quickly want to retrieve that record of the file that matches R the best. If retrieval occurs frequently on the same file, a supporting data structure is called for. This *associative file searching* problem was first posed by Knuth [1973] as a two-dimensional generalization of the usual (one-attribute) file-searching problem. It possibly is best known in its geometric version under the name post-office problem: Given a set S of n sites in the plane (post offices), report a site closest to a given query point q (the location of a person). Note that there exists a trivial $O(n)$ -time solution by computing all n distances. There are various algorithms in computational geometry that need the post office problem as a subroutine [Preparata and Shamos 1985].

Shamos [1975a] first observed the relevance of Voronoi diagrams to this problem. A site p is closest to q if and only if q falls into the region of p . In a preprocessing step the Voronoi diagram of S is computed. To report a site closest to q , it now suffices to determine the region that contains q . For this so-called point-location problem, efficient solutions have been developed by Kirkpatrick [1983], Edahiro et al. [1984], and Edelsbrunner et al. [1986]. In particular, point location in a Voronoi diagram with n regions is supported in $O(\log n)$ time and $O(n)$ storage overhead. This shows that the post-office problem can be solved by means of Voronoi diagrams in logarithmic query time and without increasing the order of space, which is well known to be optimal already for usual file searching.

Cluster Analysis

The problem of automatically clustering data arises frequently [Hartigan 1975]. Finding clusters means determining a partition of the given set of data into subsets whose in-class members are similar and whose cross-class members are dissimilar according to a predefined similarity measure. In the case of two-

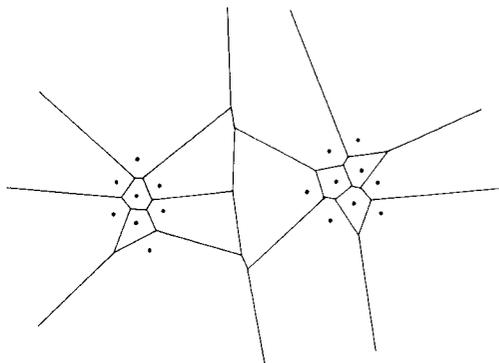


Figure 2. Voronoi diagram for two dense clusters.

attribute data, similarity is reflected by the proximity of sites in the plane. Proximity, in turn, is revealed by properties of the Voronoi diagram for these sites. For instance, dense subsets of sites give rise to Voronoi regions of small area; regions of sites in a homogeneous cluster will have similar geometric shape; for clusters having orientation-sensitive density, the shapes of the regions will exhibit a corresponding direction sensitivity. Figure 2 gives an example. Ahuja [1982] showed how to use these properties for clustering and matching sites.

Voronoi diagrams support various clustering techniques used in practice. What is required at any stage of the clustering process is often little more than the retrieval of the nearest-neighbor sites of specified sites. They can be reported easily by examining the edges of the regions of the specified sites. This applies to several hierarchical methods [Murtagh 1983], partitional methods [Asano et al. 1988], and methods involving cluster selection [Aggarwal et al. 1989].

Scheduling Record Accesses

Consider a mass storage system represented by a two-dimensional array of grid points, each capable of storing one record. The time for the read/write head to move from point (x, y) to the point (u, v) is proportional to $|x - u| + |y - v|$, the distance between these points measured

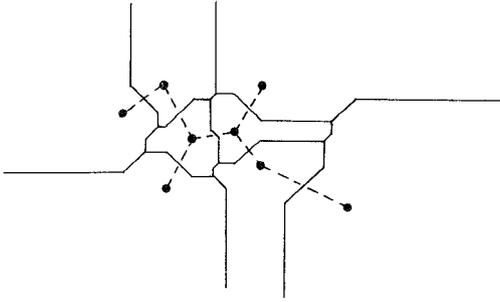


Figure 3. Voronoi diagram and minimum spanning trees in the L_1 -metric.

in the L_1 -metric (i.e., Manhattan distance). One problem that arises in accessing batched requests is the following: How is the head movement to be scheduled in order to retrieve the requested records in minimum time (distance)?

Finding an exact solution was shown to be NP-complete by Lee and Wong [1980]. A satisfactory approximate solution can be obtained quickly by means of Voronoi diagrams. In an initial step, the Voronoi diagram induced under the L_1 -metric is computed in $O(n \log n)$ time by taking the n requested grid points as sites. Now the minimum- L_1 -length tree spanned by the sites can be constructed quickly: An edge of the tree can only connect sites whose regions are neighbored in the Voronoi diagram [Hwang 1979; Lee and Wong 1980]. Figure 3 illustrates this diagram (solid) and the corresponding spanning tree (dashed). To obtain a head movement whose length is within a factor of 2 of the optimum, each tree edge is traversed twice to access all the sites.

Collision Detection

An important topic in controlling the motion of robot systems is that of collision detection. For a robot moving in an obstacle environment, one needs to determine collisions between moving robot subparts and stationary obstacles or between two separately moving subparts of the robot. In particular, *proximity detection* is important in order to be able to

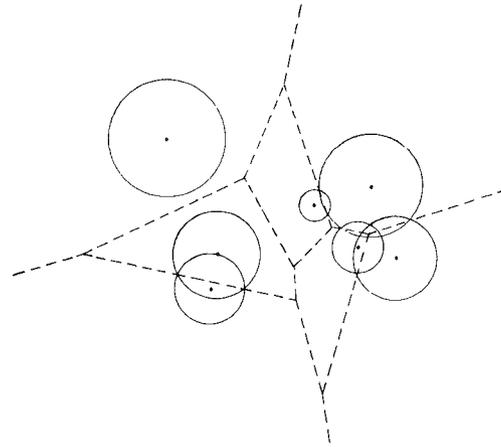


Figure 4. Power diagram for seven circles.

stop the system before a collision will have occurred.

The robot system and the environment of obstacles are usually modeled by polygonal objects. For the sake of proximity detection, collision-critical points on the boundary of these objects may be circumscribed by circles whose radii correspond to the tolerance threshold of the system. This reduces the problem to detecting the intersection of circles. Colors may be assigned to the circles in order to distinguish between “harmless” intersections (among circles stemming from the same moving robot part or the same obstacle) and others. Sharir [1985] pointed out that there will be no intersection between circles of different colors if all the connected components formed by the circles are unicolorous. Finding connected components and checking colors seem to involve an inspection of each pair of circles. The problem becomes easy, however, if the power diagram (the Voronoi diagram where the power lines of the circles are taken as separators) is available; see Aurenhammer [1988a] where this problem is solved in $O(n \log n)$ time for n colored circles. The crucial property that can be exploited is that the points of intersection of two circles lie on their common power line (Figure 4).

1. HISTORICAL PERSPECTIVE

The history of Voronoi diagrams can be traced back to the middle of the nineteenth century. Although the spectrum of scientific disciplines that include interest in Voronoi diagrams is broad, three aspects have been emphasized:

- (1) Their use in modeling natural phenomena
- (2) The investigation of their mathematical, in particular, geometrical, combinatorial, and stochastic properties
- (3) Their computer construction and representation

Accordingly, Voronoi diagrams are useful in three respects: As a structure per se that makes explicit natural processes, as an auxiliary structure for investigating and calculating related mathematical objects, and as a data structure for algorithmic problems that are inherently geometric. In all three applications, efficient and practical algorithms for computing Voronoi diagrams are required. Since the first application bears the initial seed for their investigation, let us consider the role that Voronoi diagrams play in the natural sciences first.

1.1 Natural Scientist's Viewpoint

To visualize the appearance of a Voronoi diagram in nature, one could think of the three-dimensional space being subdivided into a manifold of crystals: From several sites fixed in space, crystals start growing at the same rate in all directions and without pushing apart but stopping growth as they come into contact. The crystal emerging from each site in this process is the region of space closer to that site than to all others. In other words, the regions form a Voronoi diagram in three-space.

1.1.1 Domains of Action

Most of the early work on Voronoi diagrams was motivated by crystallography.

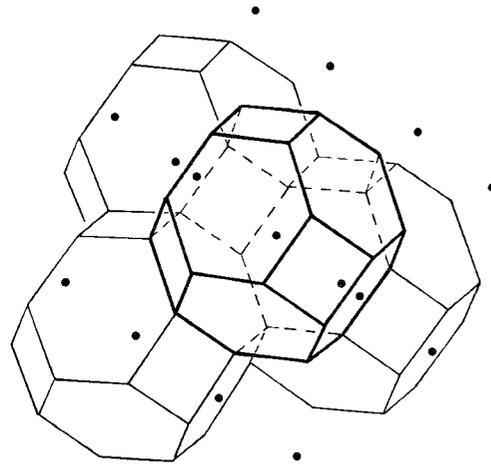


Figure 5. Cubic crystal structure.

The objective in this respect was the study of regions arising from regularly placed sites. Figure 5 illustrates some of the regions defined by 15 cubically ordered sites. In his comprehensive article on crystal structures, Niggli [1927] calls them *Wirkungsbereiche* (*domains of action*), a term widely used nowadays and used, with many synonyms, even in the 1930s as demonstrated in the clarifying note by Nowacki [1933]. Much effort has been devoted to the fundamental crystallographical question: Which types of domains of action are capable of filling the plane or three space completely if only congruent copies (and certain motions) are to be used? Significant work was done, among others, by Niggli [1927], Delaunay (Delone) [1932], Nowacki [1976], and by Koch [1975]. In fact, the question is a deep mathematical one, and we will come back to it in the discussion of mathematical aspects of Voronoi diagrams.

1.1.2 Wigner-Seitz Zones

A physicochemical system consists of a number of distinct sites, typically molecules, ions, or atoms. Equilibrium and other properties of the system depend on the spatial distribution of the

sites, which can be conveniently represented by dividing the space between them according to the nearest-neighbor rule. The resulting Voronoi regions are often called *Wigner-Seitz zones* after Wigner and Seitz [1933], who were the first to use them in metallurgy. Frank and Kasper [1958] use these zones in the investigation of complex alloy structures; Loeb [1970] bases his survey of cubic crystal structures on an intimately related concept. Allotting zones to sites is of interest to molecular physicists, biochemists, material scientists, and physical chemists. Via this approach Brostow and Sycotte [1975] estimate the coordination number of liquid argon, David and David [1982] study certain solvation structures, Brumberger and Goodisman [1983] interpret the small-angle scattering of catalysts, and Augenbaum and Peskin [1985] treat large-scale hydrodynamic codes—just to name a few.

1.1.3 Johnson-Mehl and Apollonius Model

The nearest-neighbor rule (or equivalently, the crystal growth model mentioned earlier) forces the Voronoi regions to be convex polyhedra. Allowing the crystals to start their growth at different times gives rise to hyperbolically shaped regions. The resulting *Johnson-Mehl model* was proposed by Johnson and Mehl [1939] as a more realistic model of structure for minerals. Figure 6 gives an illustration; crystals are augmented with their date of birth.

Crystals growing simultaneously but at different rates give rise to spherically shaped regions forming the *Apollonius model*. This structure can also be observed as cell structures of plants or in foams made out of soap bubbles [Matzke and Nestler 1946; Smith 1954; Williams 1968]. It further appears as covering areas of plants and as areas of best-received transmitters [Sakamoto and Takagi 1988]. Weaire and Rivier [1984] give a comprehensive survey and various statistical data. Interestingly, the equilibrium state of a spider web constitutes a generalized, although still polygonal,

Voronoi diagram. This follows from investigations by Maxwell [1864]. Figure 7 shows sites for a spider web such that the distance between neighborhood sites corresponds to the tension of the edge they define.

1.1.4 Thiessen Polygons

Geographical interest in Voronoi diagrams originates with the climatologist Thiessen [1911], who assigned proximity polygons to observation sites in order to improve the estimation of precipitation averages over large areas. His method was worked out in detail by Horton [1917] who proposed the name *Thiessen polygons*, crediting Thiessen with the idea. As reported in Boots [1979], Thiessen polygons play four roles in geographical research: As models for spatial processes, as nonparametric techniques in point-pattern analysis, as organizing structures for displaying spatial data, and for calculating individual probabilities in point patterns. In particular, we mention Tuominen [1949] and Snyder [1962] (applications to urban planning), Gambini [1966] and Boots [1979] (market areas; generalized Thiessen polygons are used there, in particular, the Johnson-Mehl and Apollonius models), Mollison [1977] (ecological contact models), McLain [1976] (spatial interpolation), Arnold and Milne [1984] (cartography), and Okabe et al. [1988] (facility location). For surveys of Thiessen polygons from a geographical and economic point of view, see Boots [1986], Eiselt and Pederzoli [1986], and Sibson [1979].

Suzuki and Iri [1986] report on the importance of recovering the sites from a given subdivision of a geographical area. This inverse process of constructing Thiessen polygons arises in the optimal outline of school districts or of voting precincts. In geographical variation analysis, connectivity graphs for sites are a valuable tool [Matula and Sokal 1980]. Among them are the minimum spanning tree or Prim shortest connection network (Figure 8), the Delaunay triangulation, and the Gabriel graph. These three

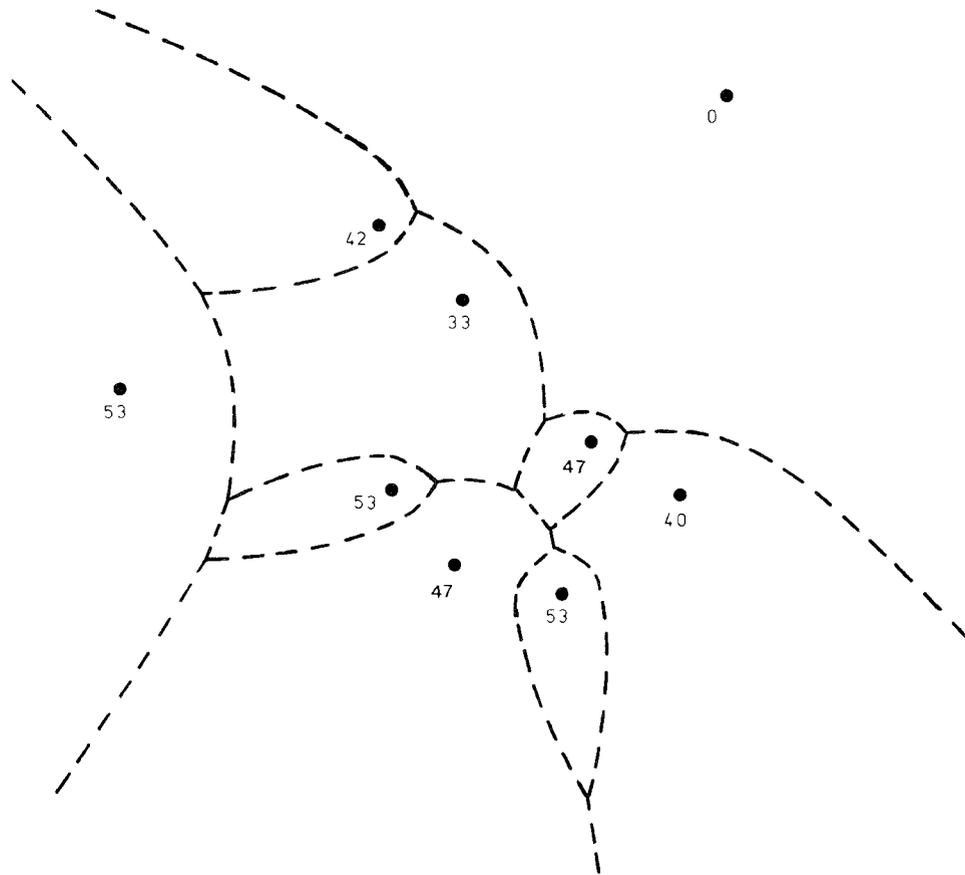


Figure 6. Johnson-Mehl model.

concepts are intimately related to Thiessen polygons as will be discussed later.

1.1.5 Blum's (Medial Axis) Transform

Yet another name for the Voronoi diagram is popular in the natural sciences: *Blum's transform* of a set of sites. Concerned with biological shape and visual science, Blum [1967] used it for modeling new descriptors of shape. In general, the main problem in pattern recognition is to extract characterizing elements from a given (site) pattern. When no geometrical model of the pattern is available, its structural description may be based on the notion of neighborhood of a site and thus, in particular, on Blum's transform. Fairfield [1979] successfully compared

contours obtained in this way with perceptual boundaries studied by Gestalt psychologists. As pointed out by Blum [1973], curvature properties of a given contour correspond to topological properties of its transform (compare Figure 9). The smooth pieces of the contour (solid) should be viewed as sites of generalized shape. By definition, each point of the transform (dashed) is equidistant from at least two sites. In this context, the transform often is called the *medial axis* or *skeleton* of the contour. The medial axis of digitized contours was exploited in image processing by Philbrick [1968], Montanari [1968], and Lantuejoul and Maisonneuve [1984].

Although the foregoing list of applications of Voronoi diagrams in the natural

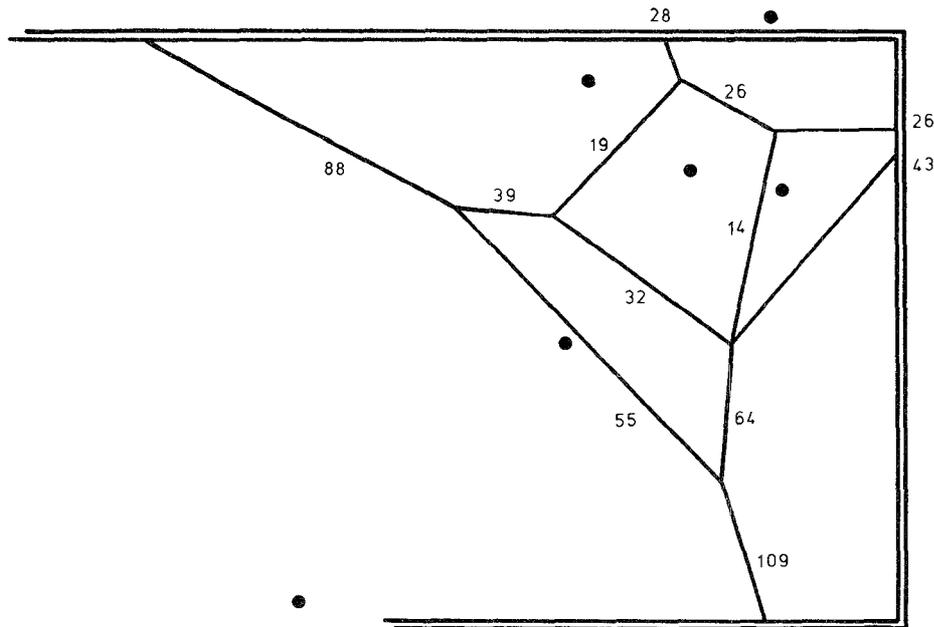


Figure 7. Spider web.

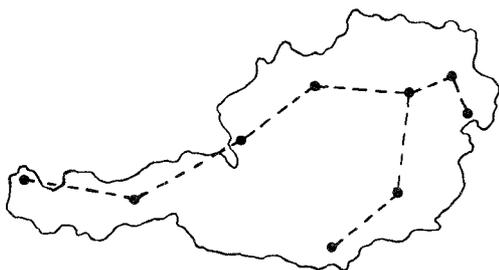


Figure 8. Minimum spanning tree for the nine state capitals of Austria.

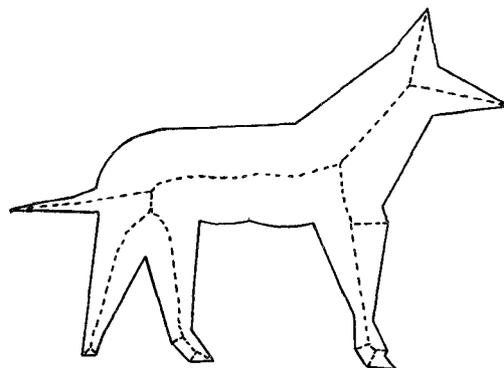


Figure 9. Contour and its medial axis [Philbrick 1968].

sciences is not complete, we refrain from further details and turn now to their role in the mathematical environment.

1.2 Mathematician’s Viewpoint

The very earliest motivation for the study of Voronoi diagrams stems from the theory of quadratic forms. Gauss [1840] observed that quadratic forms have an interpretation in terms of Voronoi diagrams for sites that are parallelotopically ordered in space. His idea was

exploited by Dirichlet [1850] to establish, among other results, a simple proof of the unique reducibility of quadratic forms. A careful generalization to higher dimensions was provided by Voronoi [1908]. To honor the pioneering work of these mathematicians, the construct has been referred to as the *Dirichlet tessellation* or the *Voronoi diagram*, and indeed

these terms are the most popular ones in the vast body of literature.

The following review provides basic mathematical properties of Voronoi diagrams and their generalizations (many of them will also be crucial in the understanding of their algorithmic properties and applications), as well as points out certain features of Voronoi diagrams that have potential applications but may be not familiar to computational geometry researchers.

1.2.1 Regularly Placed Sites

Mathematical interest in Voronoi diagrams can be divided according to whether regularly or irregularly placed sites are involved. A main area where Voronoi diagrams for regularly placed sites have been used for a long time is geometrical crystallography.

Let R^d denote the d -dimensional Cartesian space. A *tiling* of R^d is a covering of R^d by closed sets whose interiors are pairwise disjoint. Tilings of R^d by convex polyhedra with the property that the group of motions mapping the tiling onto itself is a crystallographic group [Bieberbach 1912] are of particular interest. Their polyhedra are necessarily congruent and were called *stereohedra* by Federoff [1885] and *fundamental domains* by Schönflies [1891]. One of the central questions of geometrical crystallography has been to enumerate all stereohedra and to classify them according to their crystallographic groups.

Most progress was made for the subclass of *plesiohedra*. They can be interpreted as Voronoi regions and were called *special fundamental domains* by Schönflies [1891] and *domains of action* by Niggli [1927]. Laves [1930] and Delaunay et al. [1978] enumerated all plesiohedra in R^2 . Applying a refined classification scheme, Delaunay [1932] distinguished among 24 types of plesiohedra in R^3 . A complete list of planar stereohedra was given by Grünbaum and Shephard [1987].

Delaunay [1932] showed that the number of *facets* (faces of dimension $d - 1$) of

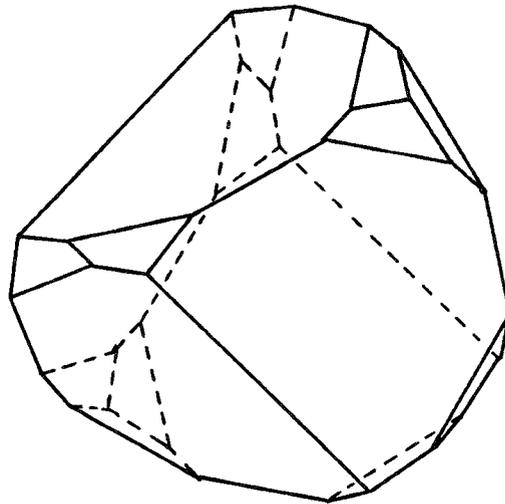


Figure 10. Plesiohedron with 18 facets [Grünbaum and Shephard 1980].

a stereohedron in R^d is finite; for instance, 390 is an upper bound for $d = 3$. So, by Tarski's [1951] decidability theorem, all spatial stereohedra can be "effectively" determined. In spite of this fact, their enumeration is still incomplete. Also, an enumeration method for plesiohedra mentioned in Delaunay [1963] does not yield a practical algorithm. Among others, Nowacki [1976], Koch [1973], and Engel [1981] discovered spatial plesiohedra with 18, 23, and 38 facets, respectively. Figure 10 depicts a plesiohedron with many facets. It seems surprising that its congruent copies are capable of filling three-space completely.

The methods used to obtain plesiohedra with large numbers of facets are probably as interesting as the numbers themselves. After carefully choosing a set of regularly placed sites (dependent of several variable parameters), certain parts of its Voronoi diagram are constructed via computer [Engel 1981]. For excellent sources on tilings, refer to Grünbaum and Shephard [1980, 1987].

It is worthwhile to mention that Voronoi diagrams for regularly placed sites also find other applications in mathematics. They apply to numerical integration [Babenko 1977], to packing

and covering problems for congruent spheres [Rogers 1964], and to statistical investigations of lattice systems [Besag 1974; Mollison 1977; Conway and Sloane 1982].

1.2.2 Irregularly Placed Sites

Let us now turn our attention to Voronoi diagrams arising from sets of irregularly placed sites. A tiling of R^d by polyhedra is called a *cell complex* in R^d if the tiling is *facet to facet*, that is, each facet of a polyhedron is also a facet of some other polyhedron in that tiling.² Every tiling of R^d by polyhedra is a cell complex. The Voronoi diagram for irregularly placed sites is still a cell complex although its regions are no longer congruent polyhedra.

This fact gives rise to various questions. Motivated by the problem of finding densest sphere packings, Rogers [1964] posed the following extremal problem: How big is the smallest possible Voronoi region with t facets and defined by sites with minimum distance two? Estimates of this and related quantities were derived by Muder [1988a, 1988b] for planar regions.

Much work on general Voronoi diagrams is concerned with their combinatorial properties and, in particular, with their size, that is, their numbers of faces of various dimensions as a function of the number n of sites considered. The size of a Voronoi diagram is an important quantity since it relates the amount of space needed to store this structure to the input size. Answering Crum's problem, Dewdney and Vranich [1977] exhibit an arbitrarily large set of Voronoi polyhedra in R^3 each pair of which shares a facet. The example they give shows that the size of a Voronoi diagram in R^3 is $O(n^2)$; this was also observed by Preparata [1977]. As already mentioned, a Voronoi diagram in the plane has size $O(n)$ since its edges and vertices form a planar

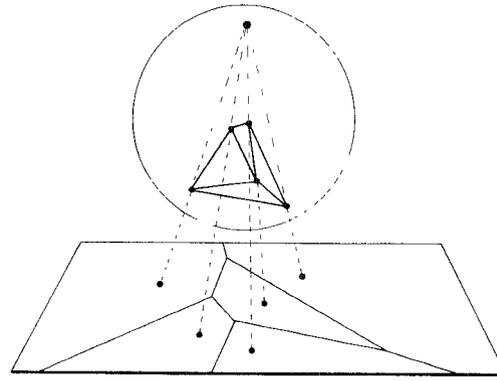


Figure 11. Voronoi diagrams are related to convex hulls.

graph. The size of higher dimensional diagrams has only recently been analyzed completely. Klee [1980] and Brown [1980] showed that Voronoi diagrams in R^d are equivalent to certain convex polyhedral surfaces in R^{d+1} in a strong sense. Hence, known results on the size of polyhedra carry over, in particular, the so-called upper and lower bound theorems [Brøndsted 1983]. Exploiting this relationship, exact bounds on the numbers of individual faces of d -dimensional Voronoi diagrams were derived by Seidel [1982] and by Paschinger [1982]. Figure 11 illustrates Brown's original transform that relates the Voronoi diagram in R^2 to a convex hull in R^3 via stereographical projection.

1.2.3 Generalized Voronoi Diagrams

Interestingly, not every convex polyhedral surface in R^{d+1} is related to a Voronoi diagram in R^d . For a more general class, a one-to-one correspondence can be established. Paschinger [1982] and Aurenhammer [1987a] showed that *power diagrams* are equivalent to the boundary projection of convex polyhedral surfaces.³ This generalization assigns a particular weight w to each of the given sites p and replaces the euclidean distance $\delta(x, p)$ between a point x and p by

² In fact, a tiling is facet to facet if and only if it is face to face for faces of any dimensions less than d [Gruber and Ryskov 1987].

³ Such projections are commonly called *Schlegel diagrams* in discrete geometry [Grünbaum 1967].

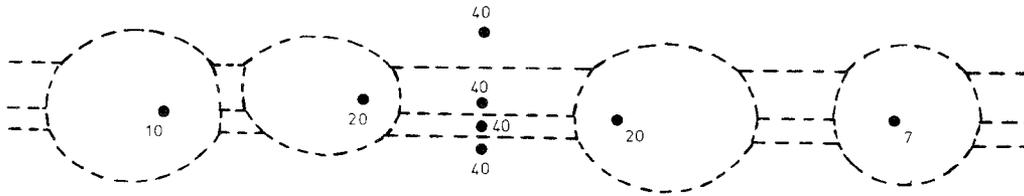


Figure 12. Apollonius model [Aurenhammer and Edelsbrunner 1984].

$\delta^2(x, p) - w$. Intuitively speaking, w expresses the capability of p to influence its neighborhood. In particular, the pair (p, w) may be interpreted as a sphere with center p and radius \sqrt{w} if $w > 0$. As an important property, the separator defined by two weighted sites in R^2 is still a straight line: the power line of two circles. Figure 4 shows a power diagram in the plane. Power diagrams already appeared in Dirichlet [1850]—therefore, often being called *generalized Dirichlet cell complexes*—and continued to be objects of interest, especially in sphere packing [Rogers 1964], illuminating spheres [Linhart 1981], and the geometry of numbers [Gruber and Lekkerkerker 1988].

The concept of weighting the sites gives rise to several other useful types of diagrams. Weighting the euclidean distance by a *multiplicative* constant yields the Apollonius model, investigated by Aurenhammer and Edelsbrunner [1984]. The separator of two sites in the plane describes their Apollonius circle. From Figure 12 it can be seen that regions may be disconnected and may partition the plane into $\Theta(n^2)$ connected components. *Additive* weights give rise to the Johnson-Mehl model (compare Figure 6). For many additional types, see Ash and Bolker [1986].

At this point, let us modify the concept of Voronoi diagram in another way. The *order- k Voronoi diagram* of n sites is a partition of R^d into regions such that any point within a fixed region has the same k closest sites. Its regions are convex polyhedra that form a cell complex in R^d . For $k = 1$, the classical Voronoi diagram is obtained. In the case of $k =$

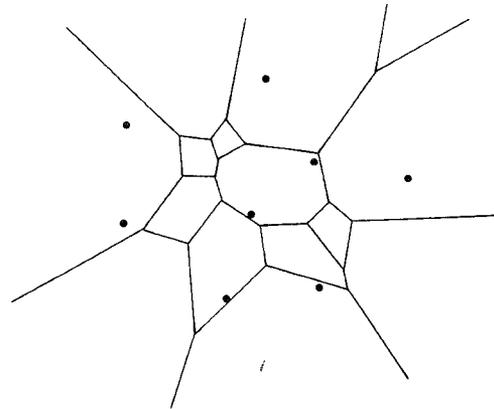


Figure 13. Planar order-2 Voronoi diagram [Shamos 1978].

$n - 1$, the structure is often referred to as the *furthest site Voronoi diagram* since now the region of a site contains all points in space furthest from it. Figure 13 shows an order-2 Voronoi diagram for 8 sites in the plane. Note that only 15 of the 28 pairs of sites define a region and that a separator may yield more than one edge. (An example of a furthest site Voronoi diagram is given in Figure 24.)

Early treatments of order- k diagrams are found in Miles [1970] and in Shamos and Hoey [1975]. Lee [1982a] succeeded in proving exact upper bounds on the maximum numbers of regions, edges, and vertices of a planar order- k Voronoi diagram. Asymptotically these numbers are $\Theta(k(n - k))$. The fascinating relationship between Voronoi diagrams, weighted diagrams, order- k diagrams, and other geometric objects was worked out by Edelsbrunner et al. [1986], Aurenhammer [1987a], and

Aurenhammer and Imai [1988]. Within this context, the concepts of power diagram and *hyperplane arrangement* play a central role. Section 3.1 is devoted to a detailed description of this material. In particular, various results on the size and on the computational complexity of constructing such diagrams are obtained. However, still little is known on the size of the order- k Voronoi diagram in higher dimensions; consult [Edelsbrunner and Seidel 1986]. Only for the furthest-site diagram exact upper bounds are available [Seidel 1987]. The number of regions of an order- k Voronoi (or power) diagram is closely related to the number of k -sets of a finite point set. Determining these numbers belongs to the main open problems in combinatorial geometry.

Once the usefulness of known types of Voronoi diagrams had been realized, further generalizations were attempted. Motivation mostly came from applications in computational geometry. In order to meet practical needs, *general distance functions* like the L_p -metrics [Lee 1980a] or convex metrics [Chew and Drysdale 1985] were taken to define a Voronoi diagram. Also, the *shape of sites* was varied while using a canonical extension of the euclidean distance function. Line segments [Kirkpatrick 1979], curve segments [Yap 1987], and disks or general convex sites [Leven and Sharir 1986, 1987] have been considered. If the segments form a closed curve, their diagram is just the medial axis of a contour (compare Figure 9). Disks can be viewed as centers weighted additively by their radii, thus giving rise to the Johnson-Mehl model. This list is not meant to be exhaustive; we shall be concerned with mathematical and computational properties of various generalized Voronoi diagrams in later sections.

Let us mention one more way of generalization: *changing the underlying space*. Ehrlich and Im Hof [1979] investigated the behavior of Voronoi regions in Riemann manifolds. Brown [1980], Paschinger [1982], and Yap [1987] observed that Voronoi diagrams on the

sphere and on the torus, respectively, are closely related to their equivalents in the euclidean space of the same dimension. Diagrams on three-dimensional polyhedral surfaces and on the three-dimensional cone have been treated by Mount [1985] and by Dehne and Klein [1987], respectively.

1.2.4 Delaunay Triangulations

Hand in hand with the investigation of Voronoi diagrams goes the investigation of related constructs. Among them, the *Delaunay triangulation* is most prominent. It contains a (straight-line) edge connecting two sites in the plane if and only if their Voronoi regions share a common edge. The structure was introduced by Voronoi [1908] for sites that form a lattice and was extended by Delaunay [1934] to irregularly placed sites by means of the empty-circle method: Consider all triangles formed by the sites such that the circumcircle of each triangle is empty of other sites. The set of edges of these triangles gives the Delaunay triangulation of the sites.

The planar Voronoi diagram and the Delaunay triangulation are duals in a graphtheoretical sense. Voronoi vertices correspond to Delaunay triangles, Voronoi regions correspond to sites, and edges of both types correspond by definition. From Figure 14 it can be seen that Delaunay edges (solid) are orthogonal to their corresponding Voronoi edges (dashed)—but do not necessarily intersect them—and that the boundary of the convex hull of the sites consists of Delaunay edges. The duality immediately implies upper bounds of $3n - 6$ and of $2n - 4$ on the number of Delaunay edges and triangles, respectively (compare Introduction). The Delaunay triangulation and its duality to Voronoi diagrams generalize to higher dimensions in an obvious way. By results by Dewdney and Vranich [1977], the Delaunay triangulation in R^3 may already be the complete graph on n sites, thus having $\binom{n}{2}$ edges. For a

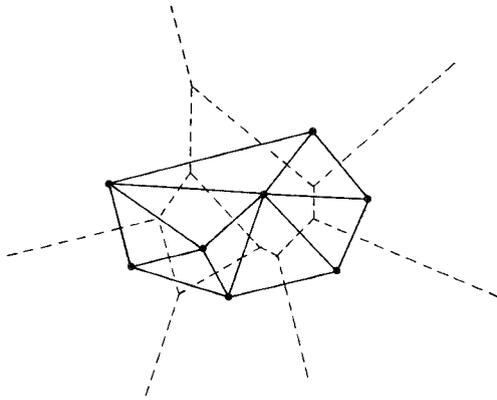


Figure 14. Voronoi diagram and Delaunay triangulation are duals.

catalog of properties of higher dimensional Delaunay triangulations arising from site lattices see Gruber and Lekkerkerker [1988].

Several interesting properties are known for the Delaunay triangulation in the plane. It was first observed by Sibson [1977] that this triangulation is *locally equiangular*. This property holds when, for any two triangles whose union is a convex quadrilateral, the replacement of their common edge by the alternative diagonal does not increase the minimum of the six interior angles concerned. Actually, the Delaunay triangulation is the only one with this property that particularly shows its uniqueness. For sites being in general position (the Delaunay triangulation may contain more-sided faces if four sites are cocircular), Edelsbrunner [1987] showed that local equiangularity is equivalent to *global equiangularity*. The triangles define the lexicographically largest list of sorted angles. A similar result holds if only the smallest angle of each triangle is considered [Lawson 1977]. Note that the Delaunay triangulation thus maximizes the minimum angle over all triangulations of a given set of sites. On the other hand, a simple example shows that the maximum angle is not minimized. It is interesting to note that, by the empty circle property, any triangulation without obtuse angles must be Delaunay. Tri-

angulations without “extreme” angles are desirable in finite element and interpolation methods.

Lawson [1972] gave a counterexample to Shamos and Hoey’s [1975] conjecture that the Delaunay triangulation has minimum total edge length. It does not even approximate the shortest triangulation [Manacher and Zobrist 1979], and in fact it may be as long as any triangulation [Kirkpatrick 1980]. It is, however, close to optimal on the average [Lingas 1986a]. A different criterion of optimality is mentioned in McLain [1976]. For each triangle, all its points should be at least as close to one of its defining sites as to any other site. This property is not shared by the Delaunay triangulation, as is claimed there.

As an important fact, the Delaunay triangulation is a supergraph of several well-known and widely used graphs spanned by a set of sites in the plane. Among them are the *minimum spanning tree* (or *Prim shortest connection network*) introduced by Kruskal [1956] and Prim [1957], the *Gabriel graph* introduced by Gabriel and Sokal [1969], and the *relative neighborhood graph* introduced by Toussaint [1980]. Section 2.4 gives definitions of these graphs and describes their interrelations.

The Delaunay triangulation can be exploited to find certain *linear combinations* among its defining sites. Each site not on the convex hull can be represented as a weighted mass center of the sites adjacent in the triangulation; see Sibson [1980] who mentions applications to surface smoothing. Aurenhammer [1988b] generalized this result to power diagrams and their order- k modifications. In particular, *Gale transforms* of the sites may be derived in this way [Aurenhammer 1990b]. Gale transforms are a versatile tool in the investigation of high-dimensional convex polyhedra [Grünbaum 1967].

The generalized Delaunay triangulation obtained from power diagrams gains in importance from the following recognition problem: Given some cell complex, can it be interpreted as a Voronoi diagram? A cell complex in R^d may be

viewed as a power diagram if and only if the cell complex admits a certain dual construct, called the *reciprocal figure* by Maxwell [1864], Crapo [1979], Whiteley [1979], and Ash and Bolker [1986]. The reciprocal figure is completely characterized by the properties of the Delaunay triangulation for power diagrams. Using reciprocal figures as a criterion, Aurenhammer [1987b] showed that several well-known types of cell complexes are power diagrams. Moreover, Voronoi diagrams can be recognized and their defining sites can be restored in an efficient way using reciprocal figures [Aurenhammer 1987c]. For a nice survey on reciprocal figures, see Ash et al. [1988]. Essentially distinct criteria for cell complexes to be classical or to be multiplicatively or additively weighted, Voronoi diagrams were proposed by Ash and Bolker [1985, 1986]. Blum [1967] first suggested that generally shaped sites could be reconstructed from the shape of the regions they define. Calabi and Hartnett [1968] elaborated on this question in some detail. Recognition problems of this kind find applications, aside from geography and economics, in statics and in computer science.

This list of geometric and combinatorial properties of Delaunay triangulations is not complete. We shall see various others while discussing applications in computational geometry.

1.2.5 Stochastic Properties

So far, we have surveyed a good deal of research on geometric and combinatorial aspects of Voronoi diagrams. Another significant stream of investigations concerns the determination of statistical data about the diagrams obtained from random distributions of sites. One of the earliest and strongest motivations for studying stochastic properties of Voronoi diagrams stems from their practical relevance to physical and chemical processes, especially in metallurgy and crystallography [Johnson and Mehl 1939]. Accordingly, most efforts concentrated on sites distributed in R^2 and in R^3 . In his valu-

able paper, Meijering [1953] derived means for the volume, the total boundary area, and the total edge length of the regions of a Voronoi diagram in R^3 arising from a *Poisson field* of sites, as well as the average number of vertices, edges, and facets. Several of these quantities are also given for the Johnson-Mehl model. Further progress was made by Gilbert [1961] who determined the variances for the volumes of such Voronoi regions. He also found some variances associated with plane or line section through regions. Based on experimental results, Kiang [1966] gave a formula for the random size distribution of Voronoi regions in R^1 , along with a conjecture for its generalization to R^2 and R^3 . The conjecture is, however, incorrect according to results in Gilbert [1961]. Figure 15 shows his obtained density functions in R^1 (solid), in R^2 (dashed), and in R^3 (dotted). Observed volume over mean volume is scaled.

Miles [1970] made a thorough study of Voronoi diagrams induced by a planar *homogenous site process*. Expectations of the edge number, edge length, perimeter, and area of the regions are given. Further results concern the Delaunay triangulation and the order- k family of diagrams. Relevant experimental data can be found in Crain [1978]. His observed frequencies of edges per polygon are of particular interest since no theoretical results are presently available. An important result by Dwyer [1989] shows that the expected number of vertices of the classical (closest or furthest site) Voronoi diagram in d dimensions is only $O(n)$ if the n sites are uniformly drawn in a hyperball. At this place, we mention only marginally that several results have been obtained that concern the behavior of Voronoi diagrams for sites being introduced in *random order* rather than being drawn by some probability distribution. We shall see such results in Section 1.3.

Space constraints preclude mentioning all related work. To name a few authors, we refer to Newman et al. [1983] (number of nearest neighbors in d dimensions), Weaire and Rivier [1984]

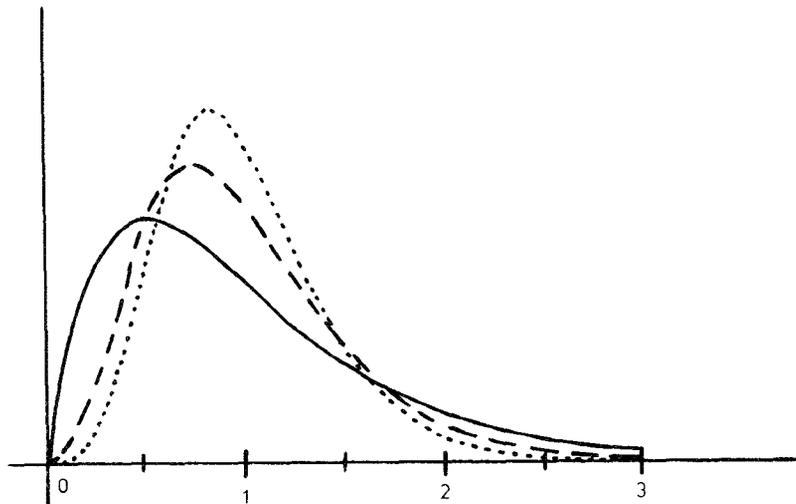


Figure 15. Empirical density function of the volume of regions [Kiang 1966].

(generalized diagrams), Besag [1974], Mollison [1977], Cruz Orive [1979], Conway and Sloane [1982] (site lattices; applications to spread of epidemics and to coding theory are given), and Aurenhammer et al. [1991] (probabilistic distance functions). The reader interested in geometrical probability in general and stochastic properties of cell complexes in particular may consult the expository papers by Moran [1966, 1969], Little [1974], and Baddeley [1977].

1.3 Computer Scientist's Viewpoint

We have documented the remarkable role that Voronoi diagrams play in the mathematical and applied natural sciences. Yet for a long time their practical usefulness suffered from the absence of reasonably simple and efficient methods for their computation. This section reviews methods for the computer construction and representation of Voronoi diagrams. Algorithmic applications of Voronoi diagrams and of related structures are discussed in Section 2.

1.3.1 Early Algorithms

Since Voronoi diagrams have been used for decades by natural scientists, many

intuitive construction rules were proposed. The earliest diagrams were drawn with pencil and ruler; see Horton [1917] or Kopec [1963] who mentions problems of ambiguity if many sites lie on a common circle. Probably the most obvious approach is to delineate the diagram in the plane region by region, by singling out those separators that contribute to edges of the current region. A provisional and admittedly inefficient version of such an algorithm was described by Rhynsburger [1973]. Other early algorithms build up the diagram vertex by vertex [Brassel and Reif 1979] or by *incremental insertion* of sites (i.e., of their regions) [Green and Sibson 1977].

Figure 16 illustrates the insertion of a site p that involves two tasks. First, we need to find the current region in which p falls. Let q be the site defining this region; the separator of p and q then will contribute an edge, e , to p 's region. Second, the boundary of p 's region (bold) is created edge by edge, starting with e . During this process, the parts of the old diagram closest to p (dashed) are traversed and deleted. These parts are specified by lying on p 's side of the separators of p and its new neighbors. If appropriately implemented, the second task requires time proportional to

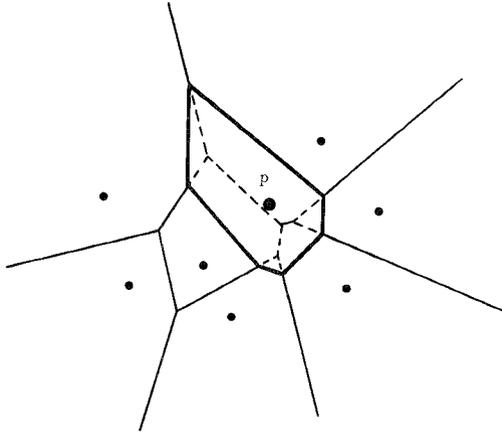


Figure 16. Inserting a Voronoi region.

the number of edges deleted. This number is $O(i)$ in the worst case (i denotes the number of sites inserted so far) since we have to delete a planar graph with at most i regions. The first task requires $O(i)$ time in the worst case, but a simple heuristic will achieve $O(\sqrt{i})$ expected time. Experimental results showed that this method is quite efficient and thus is applicable to rather large sets of sites. As for the other algorithms mentioned above, however, the worst-case behavior is $O(n^2)$ for n given sites.

Several intuitive methods are also available for the Voronoi diagram in R^3 . They compute the induced cell complex facet by facet [Brostow et al. 1978], vertex by vertex [Finney 1979], or via its dual, the Delaunay triangulation [Tanemura et al. 1983]. Potentially, they require $O(n^4)$ time in the worst case, although they may perform quite well for various distributions of sites. For $d \geq 4$ dimensions, insertion strategies working directly [Bowyer 1981] or based on the Delaunay triangulation [Watson 1981] have been used to construct a suitable combinatorial representation of the Voronoi diagram. Their time complexity is $O(n^{1+1/d})$ and $O(n^{2-1/d})$, respectively, provided the sites are “well distributed.” This should be contrasted, however, against the maximal size of a Voronoi

diagram in R^d that grows exponentially with d . A three-dimensional implementation of Watson’s algorithm is discussed in Field [1986]. Avis and Bhattacharya [1983] propose an $O(n^{\lceil d/2 \rceil + 1})$ time algorithm for determining all vertices of the d -dimensional diagram. They also outline a linear programming method for calculating the d -dimensional Delaunay triangulation but give no concrete complexity analysis.

Only recently have optimal or near-optimal algorithms for constructing Voronoi diagrams been devised. The reason is that only in the last few years have powerful algorithmic techniques been fully developed and exploited for computational geometry purposes.

1.3.2 Speeding Up Insertion

The process of building a Voronoi diagram in the plane by incremental insertion of sites stands out by its simplicity. Originally having an $O(n\sqrt{n})$ expected performance, the Green-Sibson algorithm may be polished up to run faster for several distributions of the sites. By introducing suitable orderings of the sites, the expected time for finding the region the next site falls in and for integrating the new region can be lowered to $O(1)$ [Ohya et al. 1984a, 1984b].⁴ This gives an expected runtime of $O(n)$. Clearly this is the best we can hope for because the size of the diagram is a trivial lower bound for the time needed to compute it.

An alternative approach to speeding up insertion is *randomization*. Based on a general result by Clarkson and Shor [1988], Mehlhorn et al. [1990] showed that inserting the sites in random order yields an $O(n \log n)$ -time performance with high probability. This complexity is independent of the distribution of the sites; expectation is taken over all possible permutations of the sites. The algorithm extends to the class called abstract

⁴ Recall in this context that the average number of edges of a region is less than six.

Voronoi diagrams by Klein [1989] without increase of runtime. This general concept includes power diagrams and diagrams defined by line segments or by L_p -metrics. Guibas et al. [1990] propose an even more practical version of randomized incremental construction of the classical Voronoi diagram.

As with other geometrical algorithms, the problem of numerical errors arises in the construction of Voronoi diagrams. For example, sites nearly lying on a common circle define vertices that tend to approach arbitrarily close. A proposal for making the strategy of insertion robust against numerical errors is outlined in Sugihara and Iri [1988].

The process of inserting Voronoi regions extends nicely to R^3 . Regions are convex polyhedra that can be constructed facet by facet by intersecting existing regions with separators that are planes in this case. A region cannot have more than $n - 1$ facets (one for each different site) and thus by Euler's relation, has $O(n)$ edges and vertices. Therefore, one needs $O(n + t)$ time per region if t facets, edges, or vertices are deleted during its insertion; see Aurenhammer and Edelsbrunner [1984] who treat insertions in a more general cell complex in R^3 . Since each component deleted has to be constructed first, an $O(n^2)$ -time algorithm results. This is worst-case optimal since a Voronoi diagram in R^3 may have a size of $\Theta(n^2)$.

1.3.3 Divide and Conquer

A widely used method to design fast algorithms is *divide and conquer*. Shamos and Hoey [1975] observed that this method applies well to problems in computational geometry and, in particular, to the construction of a Voronoi diagram in the plane: The given set of n sites is divided into two subsets by a vertical line. The diagrams for these subsets are computed recursively and are then "merged" in the conquer step to form the total diagram. Figure 17 shows the chain of edges (bold) to be constructed during the process of merging the diagram for

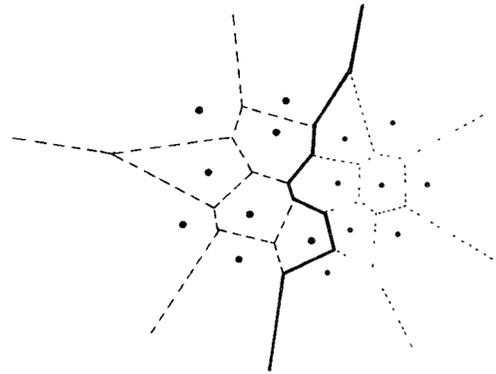


Figure 17. Merging two Voronoi diagrams [Shamos 1978].

left sites (dashed) with the diagram for right sites (dotted).

Section 3.2 is devoted to a detailed description of the method and its generalizations. In particular, two diagrams can be merged in $O(n)$ time, which implies an $O(n \log n)$ time algorithm if the divide step is carried out in a balanced way. This is worst-case optimal since any algorithm that constructs an explicit description of a Voronoi diagram may be used to sort: Interpret an input sequence of n real numbers as a set of sites on the x -axis and construct their Voronoi diagram. Regions of sites for consecutive numbers will share an edge, so the sorted sequence can be obtained in $O(n)$ time by scanning through the regions.⁵

Although theoretically fast and elegant, the divide-and-conquer approach has certain disadvantages. Implementation details are somewhat complicated, and numerical errors are likely by

⁵ Voronoi diagrams do not help for sorting general sets of sites. Seidel [1985] proved that sorting n sites in the plane with respect to their x -coordinates takes $\Omega(n \log n)$ worst-case time even when their Voronoi diagram is part of the input. It is unclear whether sorting helps for Voronoi diagrams Fortune [1988], however, pointed out that presorting the sites in two different directions lowers the additional time for constructing the diagram in the L_1 -metric to $O(n \log \log n)$.

construction: Dividing the plane into narrow slabs forces the vertices defined by sites within a slab to approach infinity. Moreover, the expected behavior is still $O(n \log n)$. An $O(n)$ -expected-time algorithm that applies divide and conquer to a certain subset of sites was outlined by Bentley et al. [1980].

Divide and conquer is the basis of a large class of algorithms for computing generalized Voronoi diagrams in the plane. Let us briefly list some of them in order to give credit to the authors who considered them first. Shamos and Hoey [1975] reported that their algorithm also applies to the furthest site Voronoi diagram in the plane. Hwang [1979], Lee and Wong [1980], and Lee [1980] considered point sites under the L_p -metrics, whereas even more general distance functions were treated by Widmeier et al. [1987], Chew and Drysdale [1985], and Klein and Wood [1988]. Imai et al. [1985] treated sites under the Laguerre distance; that is, their power diagram. Concerning the divide-and-conquer construction of Voronoi diagrams for sites more general than points, we refer to Kirkpatrick [1979] (line segments), Lee and Drysdale [1981] (line segments or nonintersecting discs), Sharir [1985] (arbitrary disks), Leven and Sharir [1987] (planar convex bodies), Yap [1987] (curve segments), and Lee [1982b] (medial axis of a simple polygon). It should be noted that most of the algorithms just mentioned are worst-case optimal.

1.3.4 Higher Dimensional Embedding

Transforming geometrical problems into more easily understood and solved ones plays an important role in computational geometry (e.g., see [Edelsbrunner 1987]). Brown [1979] first perceived the possibility of transforming Voronoi diagrams in R^2 into convex hulls in R^3 : The sites are mapped, via stereographical projection, into points lying on a sphere (compare Figure 11). This takes $O(n)$ time. The convex hull of the resulting three-dimensional point set is computed using the algorithm by Preparata and Hong

[1977] that requires $O(n \log n)$ time. The convex hull is dual to the Voronoi diagram of the given sites in a geometrical sense. Hence $O(n)$ additional time suffices for deriving the latter. This elegant approach matches the optimal $O(n \log n)$ time bound, although it suffers from the problem of processing three-dimensional objects.⁶

An important feature of the embedding method is its easy generalization to higher dimensions. Methods for determining higher dimensional convex hulls are well established [Seidel 1981, 1986], hence efficient worst-case algorithms for computing the d -dimensional Voronoi diagram become available. Their runtime, however, increases exponentially with d according to the maximal size of a diagram. This should be contrasted with a recent result by Dwyer [1989], showing that $O(n)$ expected time suffices for computing the Voronoi diagram in constant dimensions d for uniformly distributed sites.

Brown's idea was further developed by Edelsbrunner et al. [1986] for constructing the order- k Voronoi diagram family and by Aurenhammer [1987a] for constructing the power diagram and its order- k family in general dimensions. See also Edelsbrunner [1986], Aggarwal et al. [1989a], and Aurenhammer [1990a] where order- k diagrams are obtained in different ways from their higher dimensional embeddings. We refrain from any details here and refer to Section 3.1 for a comprehensive discussion of this material. For different approaches to the computation of order- k diagrams in the plane consult Lee [1982a] and Chazelle and Edelsbrunner [1987]. Clarkson [1987] speeds up a combined version of these approaches using random sampling, achieving $O(kn^{1+\epsilon})$ expected time and

⁶ In fact, since Preparata and Hong construct convex hulls by divide and conquer, this is just a three-dimensional translation of a divide-and-conquer construction. By Brown's result, simple convex hull algorithms [Clarkson and Shor's 1988] lead to simple Voronoi diagram algorithms, however.

space (for any $\epsilon > 0$) that is nearly optimal.

Embedding in higher dimensions yields algorithms for various different types of diagrams. See Aurenhammer and Edelsbrunner [1984] for the multiplicatively weighted Voronoi diagram, Aggarwal et al. [1989a] for the medial axis of a convex polygon, Edelsbrunner et al. [1989] for cluster Voronoi diagrams, and Aurenhammer and Stöckl [1988] for the peeper's Voronoi diagram.

1.3.5 Plane-Sweep Construction

Another powerful technique in computational geometry is the *plane-sweep technique* [Preparata and Shamos 1985]. In contrast to the embedding method, this technique decreases the dimension of the problem. Intuitively speaking, the static problem of computing a Voronoi diagram in the plane is reduced to the dynamic problem of maintaining the cross section of the diagram with a straight line. The algorithm simulates sweeping a line across the plane from below. At any point in time, the portion of the diagram below the sweep line is complete (Figure 18). Fortune [1985, 1987] first observed that updates on the sweep line can be implemented to cost $O(\log n)$ time if a certain continuous deformation of the diagram is treated. From this deformation, the original diagram can be constructed in $O(n)$ time. The method, its application, and its modification for generalized Voronoi diagrams are described in detail in Section 3.3.

The plane-sweep approach to Voronoi diagrams combines simplicity and efficiency. It achieves the optimal $O(n \log n)$ time and $O(n)$ space bounds for the classical type, the additively weighted type, and the diagram for line segments [Fortune 1987]. The method has been successfully applied by Seidel [1988] to Voronoi diagrams with line segment obstacles joining sites (and their constrained Delaunay triangulations). This type had been previously attacked by means of rather involved divide-and-

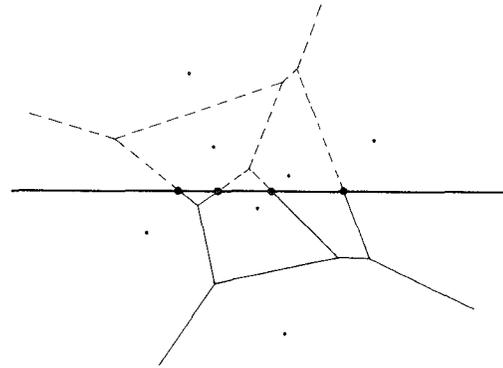


Figure 18. Maintaining the intersection with a line.

conquer algorithms [Lee and Lin 1986; Lingas 1986b; Chew 1989a; and Wang and Schubert 1987]. As was reported by Rosenberger [1988], plane sweep also performs well for planar order- k diagrams even when the sites are weighted additively.

1.3.6 Delaunay Triangulation Algorithms

Since the Voronoi diagram and the Delaunay triangulation are duals, the combinatorial structure of either structure is completely determined from its dual. Consequently, the Delaunay triangulation of n sites in the plane can be obtained in $O(n)$ time after an $O(n \log n)$ -time precomputation of the Voronoi diagram. Several practical applications, however, solely exploit combinatorial properties of the Delaunay triangulation. This has led to the investigation of methods for constructing this structure directly, thus avoiding the need to calculate and store the coordinates of Voronoi vertices.

Lawson [1972] proposed an algorithm for constructing locally equiangular triangulations by local improvement. Starting with an arbitrary triangulation of the sites, edges are “flipped” according to the equiangularity criterion (stated in Section 1.2.4) until no more such exchanges are required. Sibson [1977] succeeded in proving that this procedure

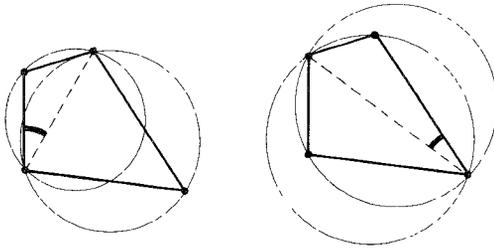


Figure 19. Equiangularity and empty circle property.

actually constructs the Delaunay triangulation. Lawson's original method was somewhat speeded up by Lee and Schachter [1980] who proceed incrementally and apply the edge flipping procedure after each insertion of a new site. McLain [1976] uses the empty circle property to construct the Delaunay triangulation by successively adding triangles whose circumcircles are empty of sites. In fact, Figure 19 illustrates the equivalence of the empty circle property and the equiangularity criterion. Although being simple to implement, all these algorithms have an $O(n^2)$ -time behavior in the worst case. On the other hand, Maus [1984] reports that a modification of McLain's algorithm based on prepartitioning exhibits an $O(n)$ expected running time for uniformly distributed sites.

Lee and Schachter [1980] gave an $O(n \log n)$ -time Delaunay triangulation algorithm; it uses divide and conquer and is similar to Shamos and Hoey's primal Voronoi algorithm. A modified implementation using prepartitioning was shown by Dwyer [1987] to run in $O(n \log \log n)$ expected time while retaining the optimal $O(n \log n)$ worst-case time; it generalizes to the L_p -metrics for $p > 2$. Drysdale [1990] modifies the divide-and-conquer approach to compute, in $O(n \log n)$ time, Delaunay triangulations generated by general convex distance functions. A recent algorithm by Guibas et al. [1990] inserts (point) sites in random order. Using a structure similar to the Delaunay tree [Boissonnat and Teillaud 1986], earlier versions of the

triangulation are maintained to facilitate the determination of the triangle covering the next site to be inserted. This practical algorithm exhibits a randomized running time of $O(n \log n)$ and is similar in spirit to Clarkson and Shor's [1988] convex hull algorithm.

The question arises as to which of the planar Delaunay algorithms can be extended to higher dimensions. We have already seen some early (although widely used) algorithms at the beginning of this section. It should be further observed that the method of higher dimensional embedding actually first constructs the Delaunay triangulation (via a convex hull), then derives the Voronoi diagram via dualization. Recently, Rajan [1991] proved a property of d -dimensional Delaunay triangulations related to equiangularity. It implies an incremental algorithm that makes the triangulation locally Delaunay after each insertion of a new site by applying a triangle-flipping procedure similar to Lawson's method in the plane. The algorithm is worst-case optimal for odd d . Whether every d -dimensional triangulation can be made Delaunay by local improvement remains open.

1.3.7 Storage Representation and Dynamization

The Voronoi diagram may be viewed as a data structure that organizes its defining sites in a prescribed manner. A host of applications of this data structure in computational geometry will be given in Section 2. Out of a number of possibilities to store the planar Voronoi diagram or, equivalently, its dual, the Delaunay triangulation, the *quad-edge structure* proposed by Guibas and Stolfi [1985] is particularly practical. Essentially, each edge is stored as a pair of directed edges. Each directed edge, in turn, stores the vertex it originates from and pointers to the previous and to the next (directed) edge of the region to its left. The quad-edge data structure provides a clean separation between topological and geometrical aspects and supports the implementation of standard techniques for

computing Voronoi diagrams, such as divide and conquer or incremental insertion. The structure has been generalized to higher dimensions by Dobkin and Laszlo [1989] (facet-edge structure in R^3) and by Brisson [1989] (cell-tuple structure in R^d). These data structures represent the incidence and ordering information in a cell complex in a simple uniform way. See also Aurenhammer and Edelsbrunner [1984] and Edelsbrunner et al. [1986] for different data structures representing cell complexes.

Like any data structure, the Voronoi diagram can be *dynamized*, that is, maintained for a set of sites that varies over time by insertion or deletion. The case of site insertion is covered by the algorithms mentioned before that build up the diagram on line by introducing new sites. Integration of a new region into the Voronoi diagram for n sites in the plane clearly costs $\Omega(n)$ time in the worst case since the region may have n edges. Gowda et al. [1983] handle insertions and deletions of sites in $O(n)$ time by means of the so-called *Voronoi-tree* that occupies $O(n \log \log n)$ space. This tree records the history of a divide-and-conquer construction of the diagram (Figure 20). Its leaves hold the sites in lexicographical order. Each inner node is associated with the diagram that comes from combining its sons' subdiagrams. The idea originates with Overmars [1981] who, however, did not give details of the method or its storage requirement. By a result by Aggarwal et al. [1989a], deletion of a given site can be performed in time proportional to the number of edges of its region.

Using the Delaunay triangulation, a planar set of sites can be organized into a hierarchical data structure, called the *Delaunay tree* by Boissonnat and Teillaud [1986]. This structure is semidynamic; it allows the insertion of sites and supports the retrieval of the triangle in which a given point falls in efficient expected and worst-case time. The Delaunay tree reflects the history of an incremental construction of the

Delaunay triangulation (Figure 21). Any triangle T destroyed by inserting a new site gets as sons (solid pointers) the new triangles sharing an edge with T . Remaining triangles adjacent to T in such an edge get the respective new triangle as a stepson (dotted pointers). Guibas et al. [1990] further developed this structure. Among other results, they showed that the expected number of structural changes of the Delaunay tree is $O(n)$ if n sites are inserted in random order into an (initially empty) Delaunay triangulation.

A different way of dynamizing Voronoi diagrams or Delaunay triangulations is to allow *movement of sites* (continuous updates) rather than their insertion or deletion (discrete updates). The Voronoi diagram of continuously moving sites will change its shape continuously, although only at "critical" points in time will the combinatorial structure of the diagram change. Aside from degenerate cases, such combinatorial changes always are local (Figure 22). An edge between two regions (here 2 and 4) collapses to a vertex and reappears between two others (1 and 3) just in the moment when the four sites involved get cocircular. In the dual environment, this process corresponds to flipping the diagonals of the quadrilateral spanned by these four sites, which is the union of two Delaunay triangles. This suggests the definition of the *Delaunay history* of a set of moving sites as the chronologically ordered list of edge flips in their Delaunay triangulation. Tokuyama [1988] considered the case of two rigidly moving sets of n and m sites, respectively. Their Delaunay history has length $O(nm)$ and can be computed and preprocessed in $O(nm \log nm)$ time in order to retrieve the Delaunay triangulation (and the Voronoi diagram) in $O(n + m)$ time at any given moment. For n sites moving in fixed but individual directions and with constant individual velocity, the Delaunay history has length $O(n^3)$. This result by Imai et al. [1989] should be contrasted with the intuitive argument that $\binom{n}{4}$ cocircularities may

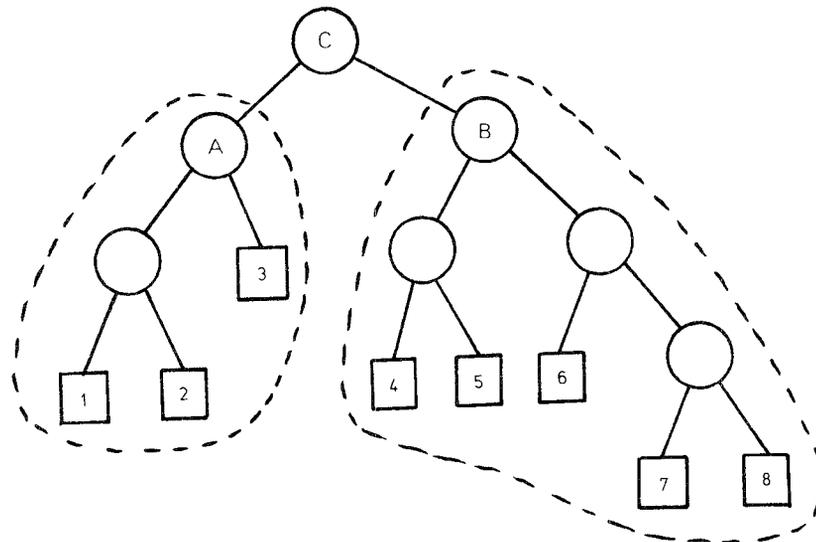
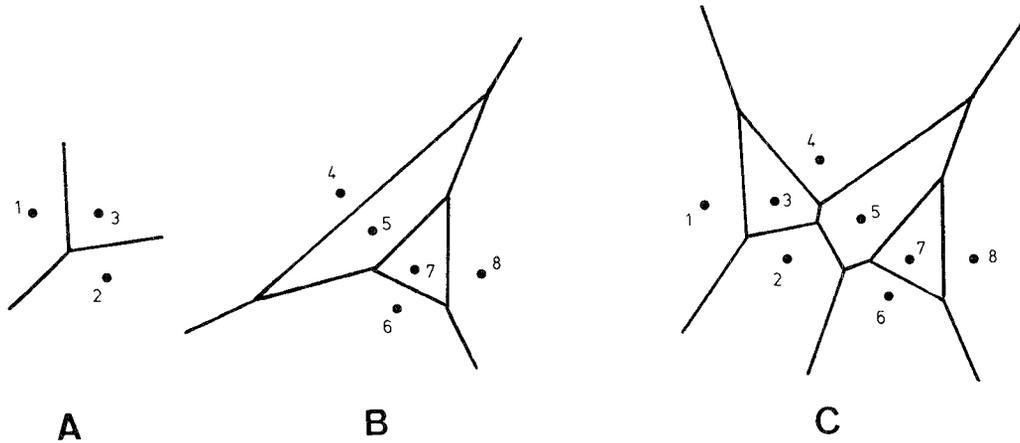


Figure 20. Voronoi tree [Gowda et al. 1983].

occur among n sites. Guibas et al. [1991] showed that the bound remains nearly cubic if the sites are moving continuously along rather general trajectories. See also Aonuma et al. [1990] for related results.

1.3.8 Computing Voronoi Diagrams in Parallel

Parallelizing algorithms in computational geometry usually is a complicated

task since many of the techniques used (incremental insertion or plane sweep, for instance) seem inherently sequential. Since it is one of the fundamental structures in this area, the Voronoi diagram has been among the first geometrical structures whose construction has been parallelized. The underlying model of computation mostly has been the CREW PRAM (concurrent-read, exclusive-write parallel random access machine), where

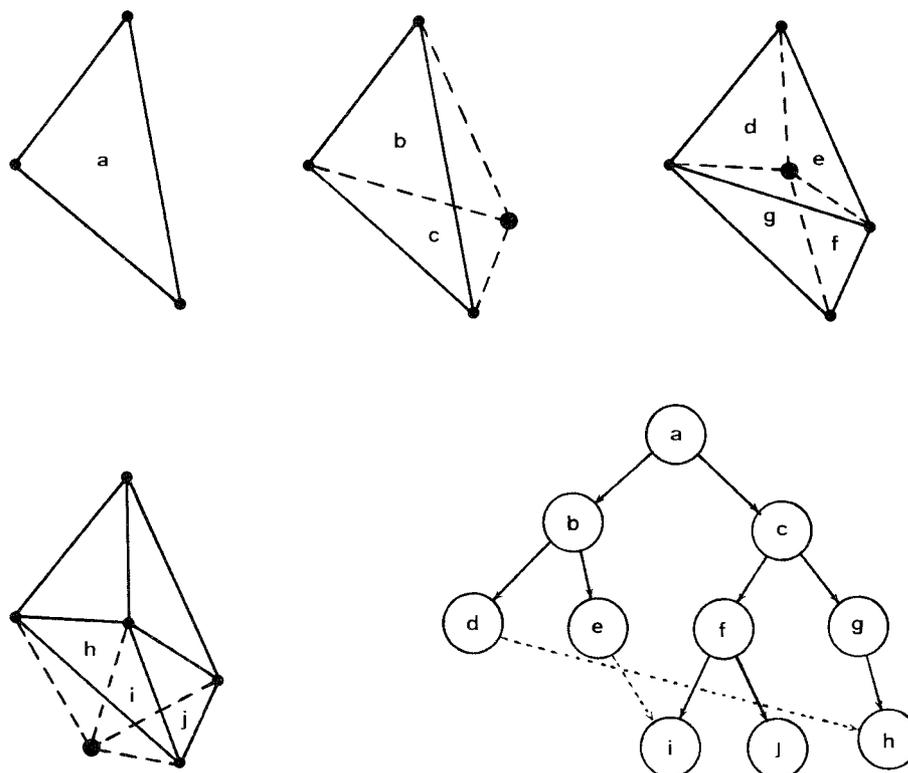


Figure 21. Delaunay tree.

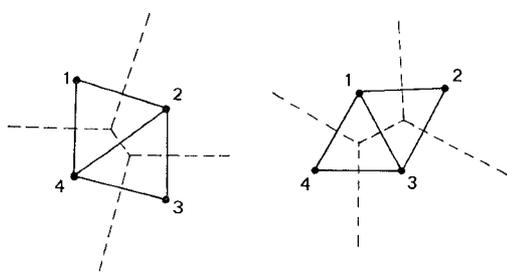


Figure 22. Combinatorial change.

processors share a common memory that allows concurrent reads but no simultaneous writes to the same cell.

As has been mentioned, $\Omega(n \log n)$ is a lower time bound for sequentially constructing the Voronoi diagram for n sites in the plane. Therefore, $O(\log n)$ parallel time is the best that can be achieved when only $O(n)$ processors are to be used.

In her pioneering work, Chow [1980] showed that convex hulls in three space can be computed in $O(\log^3 n)$ time using $O(n)$ processors. By their duality to planar Voronoi diagrams, the complexity carries over. Aggarwal et al. [1988] improved the Voronoi diagram construction to $O(\log^2 n)$ parallel time by applying divide and conquer. Their approach critically depends on restricting the domain that can contain the “merge chain” (compare Figure 17) and has been improved recently by Cole et al. [1990] using a tailor-made data structure. An optimal parallel construction of Voronoi diagrams is still outstanding, however.

Goodrich et al. [1989] construct the Voronoi diagram for line segment sites in $O(\log^2)$ time using $O(n)$ processors. Their approach to constructing this important generalization is similar in spirit to Yap’s [1987] curve segment algorithm. As a related question, Schwarzkopf

[1989] addresses the problem of computing the digitized image of a planar Voronoi diagram using certain processor networks.

2. ALGORITHMIC APPLICATIONS

The precomputation of a Voronoi diagram is the initial step of various algorithms in computational geometry. We have already mentioned some of them in the Introduction. In this part of the survey we demonstrate the broad scope of algorithmic applications of Voronoi diagrams and of closely related structures.

2.1 Closest-Site Problems

According to their definition, Voronoi diagrams apply naturally to various proximity problems. Determining closest sites plays a dominant role in this context since it appears as a subroutine of many geometric algorithms. Applications include clustering and contouring and various other problems whose relation to proximity may not be so obvious.

2.1.1 Nearest-Neighbor Queries

Probably the most popular problem in this area is the *post-office problem*. How should a fixed set of n sites in the plane be preprocessed in order to determine quickly the site closest to an arbitrarily chosen point (the query point)? The post-office problem is motivated in the Introduction as a two-dimensional file-searching problem. Another important application stems from a common data classification rule that requires assignment of new data points to the same class in which their nearest neighbor lies. An early solution yielding $O(\log n)$ query time but requiring $O(n^2)$ storage was provided by Dobkin and Lipton [1976]. Shamos [1975] pointed out that the Voronoi diagram of the sites divides the plane into regions of equal answer with respect to the post-office problem: By definition, the region of a site contains all points closer to this site than to all other

sites. This reduces the problem to finding the region that contains the query point, an approach that became powerful once efficient data structures were developed for the latter problem: point location in planar straight-line graphs [Kirkpatrick 1983; Edahiro et al. 1984; and Edelsbrunner et al. 1986]. Actually, logarithmic query time and linear storage are achieved. This is asymptotically optimal since it matches the information-theoretical lower bound.

Shamos' approach in conjunction with Kirkpatrick's was worked out in a geometrically dual setting by Edelsbrunner and Maurer [1985]. Usage of a structure related to Boissonnat and Teillaud's [1986] Delaunay tree even obviates the need of postprocessing the Voronoi diagram for point location; Guibas et al. [1990] show that post-office queries are supported in $O(\log^2 n)$ expected time by this structure. An off-line solution to the post-office problem (all query points are given in advance rather than being specified on line) was presented by Lee and Yang [1979].

In principle, higher dimensional variants of the post-office problem may be solved via the Voronoi diagram, too. Their practical relevance is evident from the equivalent file-searching problem for multiattribute data mentioned in the Introduction. Although Chazelle [1985] showed that point-location in a Voronoi diagram in R^3 can be performed efficiently, the approach suffers from a considerable storage overhead of $\Theta(n^2)$ that comes from the worst-case size of the diagram. In $d > 3$ dimensions, the prohibitively large size of the diagram may be reduced to some extent for that purpose [Dewdney 1977].

Generalizations of the post-office problem for nonpoint sites or for modified distance functions may be solved by means of an appropriate Voronoi diagram as well. We particularly mention Mount [1986] (geodesic distance on a polyhedral surface) and Aurenhammer et al. [1991] (probabilistic distances in the plane) as two generalizations leading to interesting types of diagrams.

2.1.2 *k*-Nearest-Neighbor Queries

An obvious and important generalization of the post-office problem is to ask for the *k* closest sites for a query point. It was observed by Shamos and Hoey [1975] that the order-*k* Voronoi diagram divides the plane into regions of equal answer with respect to this problem. Postprocessing the diagram for point-location yields a data structure that handles queries in $O(\log n + k)$ time and requires $O(k^2 n)$ storage. [The diagram may contain $\Theta(k(n - k))$ regions for each of which the *k* closest sites are stored.] If *k* is specified in the input, an $O(n^3)$ -space data structure yielding the same query time was obtained by Edelsbrunner et al. [1986] via embedding the whole family of order-*k* Voronoi diagrams for the sites into an arrangement of planes. A technique for compacting order-*k* Voronoi diagrams recently developed by Aggarwal et al. [1990] drastically reduces the storage requirement of these approaches [to $O(n)$ for fixed *k* and to $O(n \log n)$ if *k* is in the input] while still achieving the optimal $O(\log n + k)$ query time.

A related problem is the *circular retrieval* problem that requires a report of all sites covered by a given query disk. In facility location, for example, one might be interested in all sites being influenced by a new facility of given radius of attraction. First steps toward a satisfactory solution were undertaken by Bentley and Maurer [1979]. Their method is based on a certain sequence of order-*k* Voronoi diagrams of the given sites and has been refined by Chazelle et al. [1986b] and recently by Aggarwal et al. [1990]. The latter refinement yields a data structure using $O(n \log n)$ space and achieving $O(\log n + t)$ query time, where *t* is the number of sites in the query disk.

2.1.3 *Closest Pairs*

Finding the *closest pair* among *n* sites certainly belongs to the most fundamental proximity problems. One obvious application arises in collision detection; the two closest sites are in the greatest dan-

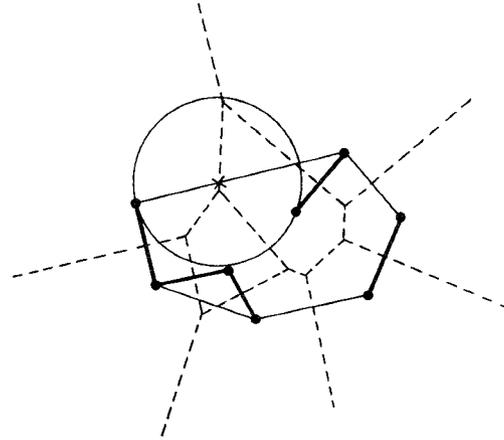


Figure 23. All closest pairs and the largest empty circle.

ger of collision. In other applications, for example, in clustering, one needs to find the closest site for each of the sites. The straightforward approach clearly results in calculating $\Theta(n^2)$ distances. In the planar case, both questions were settled in optimal time $O(n \log n)$ by Shamos and Hoey [1975] by precomputing the Voronoi diagram of the sites. See Figure 23 depicting all closest pairs by bold segments. Since the region of a site and the region of its closest site always share an edge, one only needs to visit each edge and calculate the distance between the two sites whose separator yields that edge. This clearly takes $O(n)$ time once the diagram is available. Recently, Hinrichs et al. [1988a, 1988b] showed that it suffices to maintain certain parts of the diagram during a plane sweep rather than to compute the diagram explicitly in order to solve both problems in optimal time. Curiously, the *furthest pair* of sites cannot be derived directly from the furthest site Voronoi diagram but requires some additional point-location [Toussaint and Bhattacharya 1981]. Finding the furthest pair means determining the diameter of the underlying set of sites and thus has several applications.

2.2 Placement and Motion Planning

Voronoi diagrams have the property that each point on a Voronoi edge maximizes the distance to the closest sites. Although being straightforward, this property is essential for the usefulness of Voronoi diagrams in placement and motion planning problems.

2.2.1 Largest Empty Figures

The *largest empty figure* problem is the following: Given n point sites in the plane, where should a figure of prescribed shape be placed so that its area is maximized but no site is covered? If the figure is a circle, the problem can be reformulated as finding a new site being as far as possible from n existing ones. Shamos and Hoey [1975] mentioned the relevance of this facility location problem to operations research and industrial engineering. They also showed how to find a largest empty circle in $O(n \log n)$ time: The center of such a circle is either a vertex of the Voronoi diagram of the sites or the intersection of a Voronoi edge and the boundary of the convex hull of the sites; see Figure 23 illustrating the occurrence of the latter case. Thus attention can be restricted to $O(n)$ possible placements of the circle.

The *smallest enclosing circle* of the sites is obtainable in $O(n \log n)$ time in a similar manner. Shamos [1978] claimed that this circle always will be centered at a vertex of the furthest site Voronoi diagram. This was proved true by Toussaint and Bhattacharya [1981]. From Figure 24 it can be seen that the edges of this diagram form a tree structure. This restricts the maximum number of vertices, and thus of placements of the circle, to $n - 2$.⁷ On both problems, there exists

⁷ It is easily seen that the regions of the furthest site diagram are either unbounded or empty. The corresponding *furthest site Delaunay triangulation* thus is an outer planar graph (with at most n sites as vertices), which is well known to contain at most $2n - 3$ edges and $n - 2$ triangles.

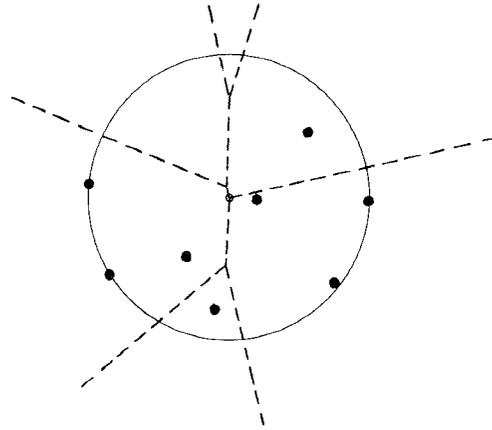


Figure 24. Furthest site Voronoi diagram and smallest enclosing circle.

a considerable literature [Preparata and Shamos 1985]. In particular, the problems are solvable in $O(n)$ time by means of linear programming as was demonstrated by Megiddo [1983].

The Voronoi diagram approach generalizes—while still achieving the $O(n \log n)$ -time bound—to other figures provided these are “circles” with respect to the underlying distance function. For example, the largest empty axis-parallel square can be found using the Voronoi diagram in the L_∞ -metric. Chew and Drysdale [1985] find largest empty *homothetic copies* of generally shaped convex figures via diagrams that are induced by a rather general class of distance functions. The determination of the largest empty axis-parallel rectangle turns out to be somewhat more complicated; the aspect ratio of the rectangle, and thus the distance function to be used, is not known in advance. This problem has an obvious application. If we are given a piece of fabric or sheet metal and the sites are flaws, what is the largest area rectangular piece that can be salvaged? Chazelle et al. [1986a] gave an $O(n \log^3 n)$ -time solution. They use an interesting type of Voronoi diagram that can be interpreted as the power diagram of a certain set of circles [Edelsbrunner and Seidel 1986; Aurenhammer and Imai 1988]. The running time above was

improved to $O(n \log n)$ by Aggarwal and Suri [1987] using different methods. The properties of the Voronoi diagram for line segment sites have been exploited by Chew and Kedem [1989] to find the largest *similar copy* of a convex polygon such that no segment is overlapped. As a related question, Aonuma et al. [1990] place a given convex polygon inside and as far as possible from the boundary of an arbitrary polygon. Their algorithm relies on Voronoi diagrams dynamized with respect to certain site movements.

2.2.2 Translational Motions

Voronoi diagrams are an aid in the planning of *collision-free motions* of a figure in the presence of obstacle sites. Problems of this kind arise in robotics. The Voronoi diagram approach plays an important role in this area and is called the retraction method. Intuitively speaking, when moving on the edges of the Voronoi diagram the robot always keeps as far as possible from the neighboring obstacles. This was first perceived by Rowat [1979]; several authors pursued this idea further.

For many applications it is feasible to approximate the scenario of obstacles by polygonal sets. O'Dunlaing and Yap [1985] plan the motion of a disk between two given points in this environment. In a preprocessing step, the Voronoi diagram of the obstacles is computed by taking their n boundary segments as its defining sites. The graph formed by the $O(n)$ straight or parabolic edges of the diagram can be computed in $O(n \log n)$ time [Kirkpatrick 1979; Fortune 1987]. Figure 25 depicts the graph (dashed) for four line segment obstacles (bold). Observe that each point on an edge is equidistant from its two closest obstacles. Therefore, for each edge, it is easy to compute the minimum clearance when moving on it. To produce a collision-free motion (if it exists), one first finds the edges e and e' closest to the center of the disk in initial and final position, respectively, and then searches the graph starting with e until either e' is reached or

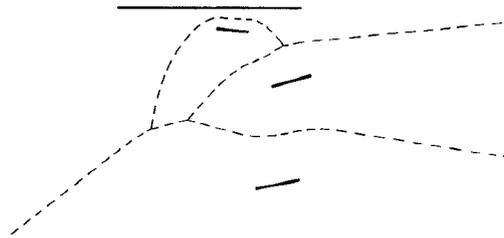


Figure 25. Voronoi diagram for line segments.

the clearance falls short of the disk radius. All of that can be done in additional $O(n)$ time.

Compared to others, this simple approach has the additional advantage that the disk radius need not be known during the preprocessing phase. Extending the approach, Leven and Sharir [1987] plan translational motions of a convex planar robot in $O(n \log n)$ time. Note that generally shaped robots may be circumscribed by a convex figure, and paths feasible for the figure will do for the robot as well.

2.2.3 Rotational Motion

Allowing the robot to rotate adds a third degree of freedom to the problem. Much attention has been paid to moving—amidst polygonal obstacles—a line segment that is allowed to rotate. The position of a segment (of given length) in the plane is determined by the triple $p = (x, y, \varphi)$ indicating the coordinates of one endpoint and the orientation. The set of all triples p such that the corresponding segment $L(p)$ does not collide with any obstacle is a subset of the underlying three-dimensional configuration space. Within this subset, we may define a Voronoi diagram as the set of all p such that $L(p)$ is equidistant from its two closest obstacles; closeness is with respect to the minimum distance between segment and obstacle.

O'Dunlaing et al. [1986, 1987] provided a thorough analysis of this diagram (which seems to belong to one of the most complex types). In particular, they showed that the diagram can be

constructed, and a motion be planned in $O(n^2 \log n \log^* n)$ time, thus being a significant improvement over earlier techniques. Sifrony and Sharir [1986] speeded up the method—by introducing a related graph—to run in $O(t \log n)$ time, where $t = O(n^2)$ is a parameter dependent on the segment length. Canny and Donald [1988] simplified the method by relaxing the definition of the diagram.

There are several other versions of the motion planning problem to which Voronoi diagrams apply [Rohnert 1988]. An axiomatic characterization of the boundary properties of a generally shaped three-dimensional scenario in order to define a Voronoi diagram suited to motion planning was proposed by Stifter [1989]. For a more detailed introduction and review of the use of Voronoi diagrams in motion planning, the interested reader may consult Schwartz and Yap [1986] or Alt and Yap [1990].

2.2.4 Path Planning

A special case of planning collision-free motions, where the robot is taken to be a single moving point, is *path planning*. Finding euclidean shortest paths in the presence of polygonal (or polyhedral) obstacles has received particular interest. For example, consider the problem of determining that location, for each of m fixed locations within a polygonal factory floor, reachable on the shortest path. This problem can be solved in $O(n + m) \log^2(n + m)$ time by first constructing the Voronoi diagram of n sites under the geodesic metric interior to a simple polygon with m edges [Aronov 1989]. The site yielding the shortest path to a particular site defines a neighboring region in the diagram. This improves an earlier result by Asano and Asano [1986]. Related questions can be solved by means of the furthest site geodesic Voronoi diagram inside a polygon; Aronov et al. [1988] showed how to construct this structure efficiently.

The following important question is still unsolved. Is it possible to compute the geodesic Voronoi diagram for n sites

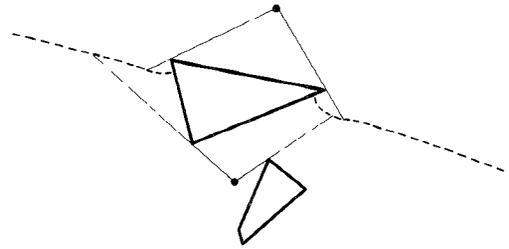


Figure 26. Geodesic separator.

and a collection of disjoint and convex polygons with a total of m edges in $O(n + m) \log(n + m)$ time? The main problem in this respect is that computing geodesic distances is not a constant-time operation. Figure 26 shows the separator (dashed) of two sites under the geodesic distance among two convex polygons (bold). It is composed of straight line and hyperbola segments meeting at intersections with visibility lines (solid).

Path-planning problems in three-dimensional polyhedral spaces have been studied, by among other authors, Mount [1986], Mitchell et al. [1987], and Baltsan and Sharir [1988]. For example, finding shortest paths lying entirely on a (generally nonconvex) polyhedral surface is of interest in areas like autonomous vehicle navigation, where hilly terrains are being modeled. Efficient solutions are obtained by using Voronoi diagrams defined in such spaces. Moreover, since finding shortest paths is closely related to determining visibility between obstacles, Voronoi diagrams involving visibility constraints have been exploited in this context. An example is the peeper's Voronoi diagram used by Baltsan and Sharir [1988] and by Aronov [1989]. Each point in the plane is assigned to the closest visible site, and visibility is constrained to a segment on a line avoiding the convex hull of the sites (see Figure 36). This structure can attain a size of $\Theta(n^2)$ and is constructable in $O(n^2)$ time [Aurenhammer and Stöckl 1988].

2.3 Triangulating Sites

Intuitively speaking, *triangulating* n sites in the plane means partitioning the

plane into triangles whose vertices are all and only the sites. Triangulations are important because they (as being planar graphs) on the one hand have only linear size and, on the other hand, establish connectivity information among the sites that suffices for many applications.

2.3.1 Equiangular Triangulations

An early and major application is the interpolation of functions of two variables, where function values initially are known only at irregularly placed sites. Practical evidence stems from finite element methods or from processing graphical data, for example, in terrain modeling. Given a triangulation of the sites, the function value at an arbitrary point can be computed by interpolation within the triangle containing that point. Lawson [1972] and McLain [1976] have reported that a triangulation is well suited to interpolation if its triangles are nearly equiangular. The Delaunay triangulation is the unique triangulation that is optimum in this sense [Sibson 1977]. Sibson [1980] further suggests the use of local coordinates obtained from sites being adjacent in this triangulation in order to compute smooth surfaces. There might, however, occur more-sided polygons (rather than triangles) if various sites are cocircular. Mount and Saalfeld [1988] showed how to triangulate such polygons in order to retain equiangularity. This process does not affect the $O(n \log n)$ time needed for constructing the Delaunay triangulation.

Given a set of sites and a particular function value (height) at each site, any triangulation of the sites defines a triangular surface in space. The “roughness” of such a surface T may be measured by the *Sobolev seminorm*

$$\sum_{\Delta \in T} |\Delta| (\alpha_{\Delta}^2 + \beta_{\Delta}^2),$$

where $|\Delta|$ denotes the area of the spatial triangle Δ , and α_{Δ} and β_{Δ} denote the slopes of the plane containing Δ . By exploiting equiangularity, Rippa [1990] showed that the Sobolev seminorm is

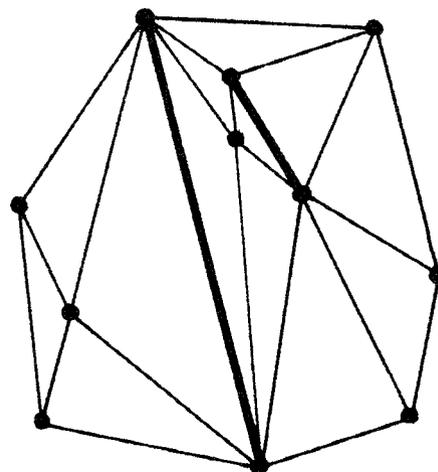


Figure 27. Constrained Delaunay triangulation.

minimized if the underlying triangulation of the sites is Delaunay. This result is somewhat surprising since the Delaunay triangulation—although itself clearly being independent of the height at each site—optimizes a quantity that depends on these heights.

2.3.2 Constrained Triangulations

In a *constrained* Delaunay triangulation, prescribed edges are forced in as part of the triangulation. See Section 3.3 for a formal definition. Figure 27 depicts such a triangulation with two prescribed edges (bold). This structure can be constructed in $O(n \log n)$ time [Seidel 1988] and has two major applications. First, it provides a more realistic approach to modeling terrain surfaces since salient elements like mountain ridges or valleys may be prescribed. Lee and Lin [1986] showed that the equiangularity criterion is still fulfilled by constrained Delaunay triangulations. Since triangles with small angles produce a poor computer graphics display, the best possible visualization is achieved. Triangulations inside a simple polygon are an important special case. The boundary edges of the polygon will not be edges of the (unconstrained) Delaunay triangulation of the polygon vertices, in general, and thus have

to be prescribed.⁸ Chew [1989b] used constrained Delaunay triangulations to generate triangular meshes inside polygons where all angles are between 30° and 120° .

Second, constrained Delaunay triangulations are an aid in path planning. In order to plan a path from A to B that avoids a set of n line segment obstacles (and thus arbitrarily shaped polygonal regions, for instance) one might construct this triangulation—by taking A and B and the segment endpoints as sites and the segments as prescribed edges—and then search the graph formed by triangulation edges. This was observed by Chew [1986], who also proved the following interesting result: Between any two sites there is a path in this triangulation whose length is at most $\sqrt{10}$ times the geodesic distance between them, provided the L_1 -metric (instead of the euclidean) is taken to define the triangulation. This yields an $O(n \log n)$ -time algorithm for approximating the optimal path, which is a significant improvement over exact methods.

Dobkin et al. [1990] proved a factor of about 5 for (nonconstrained) euclidean Delaunay triangulations and the euclidean distance. Their result has been improved to a factor of about $\frac{5}{2}$ by Keil and Gutwin [1989]. Results of this kind are rather surprising since they show the existence of a sparse graph being almost as “good” as the complete graph on n sites, independently of n .

Let us mention another application. Given n sites and some prescribed (non-crossing) edges between them, a diagonal is a new edge that does not cross any prescribed one. A popular heuristic for triangulations with minimum total edge length is the greedy method. This method

iteratively adds shortest diagonals by considering the current (and initially empty) set of edges as prescribed. Lingas [1989] reports that a shortest diagonal can be found in $O(n)$ time given the constrained Delaunay triangulation. This gives an $O(n^2 \log n)$ -time and $O(n)$ -space algorithm for constructing such *greedy triangulations*. Previous methods required $O(n^2)$ space. Whether a minimum length triangulation for n sites in the plane can be computed in polynomial time is an important open question.

2.3.3 3D Triangulations

The problem of “triangulating” point sites in three-space arises in the decomposition of three-dimensional objects, for example, of computer-generated solid models or of objects specified by planar cross sections. Field [1986], Boissonnat [1988], and others report on advantages of tetrahedral decompositions and propose the use of the Delaunay triangulation. Although there is some evidence for the quality of thus produced tetrahedra, some important properties of the two-dimensional Delaunay triangulation do not carry over.

First, the number of tetrahedra may be $\Theta(n^2)$, hence leading to a storage requirement that is prohibitive for many applications. This fact suggests the use of postprocessing. Chazelle et al. [1990] showed the following somewhat counter-intuitive result: The number of tetrahedra may always be lowered to about $n\sqrt{n}$ by adding about \sqrt{n} new sites. This process will also eliminate elongated (and thus undesirable) tetrahedra. In fact, adding $O(n)$ (well-chosen) sites will always reduce the size of the triangulation to $O(n)$, with the additional effect that only constantly many edges emanate from each site [Bern et al. 1990].

Second, the question of finding a three-dimensional analog to the equianularity property is still unsettled. Rajan [1991], however, recently succeeded in proving a related property. The three-dimensional Delaunay triangulation minimizes the largest *containment*

⁸ It is an interesting question how many new sites have to be placed on the polygon boundary in order to force it in as a subgraph of the Delaunay triangulation. Schwarzkopf (personal communication, 1990) observed that $\Omega(n^2)$ sites may be necessary for an n -vertex polygon. A known upper bound is $2^{O(n \log n)}$. The $O(n)$ bound claimed in Boissonnat [1988] involves a constant depending on the angles of the polygon.

radius of the tetrahedra; that is, the radius of the smallest sphere containing a tetrahedron. This sphere coincides with the circumsphere if and only if its center lies within the tetrahedron. Note that the containment radius measures the tetrahedron size more appropriately than the circumradius since small but elongated tetrahedra may have arbitrarily large circumradii. The Delaunay triangulation is the most compact triangulation in this sense. This property is quite remarkable as—unlike the two-dimensional situation—the number of tetrahedra is not independent of the way of triangulating the given sites but may vary from linear to quadratic.

There is another property of Delaunay triangulations that turns out to be useful in three-dimensions. For a set of triangles in three-space, an in-front/behind relation may be defined with respect to a fixed viewpoint. Generalizing a result by De Floriani et al. [1988], Edelsbrunner [1989] proved that this relation is acyclic for the triangles in a three-dimensional Delaunay triangulation, no matter where the viewpoint is chosen. This is relevant to a popular algorithm in computer graphics that eliminates hidden surfaces by first ordering the three-dimensional objects with respect to the in-front/behind relation and then drawing them from back to front, thus over-painting invisible parts. For Delaunay triangles, such an ordering always will exist, which is quite important in view of their frequent use in practice. In particular, so-called α -shapes are made of such triangles. α -shapes have been used by Edelsbrunner et al. [1983] to model the shape of point sets.

2.4 Connectivity Graphs for Sites

The Delaunay triangulation contains, as subgraphs, various structures with far-ranging applications. We will briefly discuss some of them in the sequel.

2.4.1 Spanning Trees

Given n point sites in the plane, a (euclidean) *minimum spanning tree* is a

straight-line connection of the sites with minimum total edge length. See Figure 8 for an illustration. Not surprisingly, this structure plays an important role in transportation problems, pattern recognition, and cluster analysis. Construction methods working on general weighted graphs have been known for a long time; see Kruskal [1956], Prim [1957], and, more recently, Yao [1975] whose algorithm works in $O(m \log \log n)$ time for a graph with m edges. All these algorithms use a basic fact: For any partition of the sites into two subsets, the shortest edge (edge of minimum weight) between the subsets will be present in the tree. Applying Yao's algorithm directly to the complete euclidean distance graph for the sites results in an $\Omega(n^2)$ running time, however.

Shamos and Hoey [1975] recognized that the edges of a minimum spanning tree must be Delaunay edges. This interesting and important property holds since, by the fact mentioned above, each tree edge is the diameter of a disk empty of sites and, by definition, each triangulation edge is a chord of some disk empty of sites. From the computational viewpoint, Yao's algorithm just needs to be applied to the Delaunay triangulation—a graph with $O(n)$ edges. In fact, $O(n)$ time suffices to derive the minimum spanning tree from the Delaunay triangulation [Preparata and Shamos 1985]. This gives an $O(n \log n)$ -time algorithm, which is optimal by reduction to sorting n real numbers.⁹

The relationship above extends to more general metrics. For example, Hwang [1979] extends it to the L_1 -metric (compare Figure 3). One may be tempted to conjecture that the (euclidean) *maximum spanning tree* can be obtained from the furthest site Delaunay triangulation of the sites (the dual of the furthest site

⁹ The minimum spanning tree should not be confused with the *minimum Steiner tree* of a set of sites, a concept where the addition of new points is allowed in order to minimize the total edge length. The problem of constructing a minimum Steiner tree is NP-complete [Garey et al. 1976].

Voronoi diagram). Shamos [1978] showed that this conjecture is erroneous. Eppstein [1990], however, pointed out that two sites are connected in one of the k smallest spanning trees only if both belong to the same subset of sites defining a region of the order- $(k + 1)$ Voronoi diagram. This leads to an improved algorithm for finding the k smallest spanning trees.

The efficient construction of the minimum spanning tree in three space has turned out to be a difficult problem. Pre-computation of the Delaunay triangulation does not help in general since the complete graph may be the output in the worst case. Efficient approximation and expected-time algorithms were given, among other authors, by Vaidya [1988a] and Clarkson [1989]. The first algorithm running in subquadratic worst-case time is due to Yao [1982]; it can be speeded up to run in $O(n \log n)^{1.5}$ time by using Voronoi diagrams of carefully chosen groups of sites. By exploiting—in addition—an interesting relation to a certain closest point problem, Agarwal et al. [1990] were able to bring down the complexity to $O(n^{4/3} \log^{4/3} n)$. It still remains open whether an algorithm matching the best currently known lower bound of $\Omega(n \log n)$ can be developed.

2.4.2 Spanning Cycles

A graph connecting n sites is called *Hamiltonian* if it contains some cycle passing through all the sites. The question of whether the Delaunay triangulation in the plane is Hamiltonian arose in pattern recognition problems where a reasonable simple curve through the given sites is desired. Although counter-examples were given by Kantabutra [1983] and Dillencourt [1987a, 1987b], Delaunay triangulations have been used with success for this problem. This gives evidence that this graph is Hamiltonian with high probability. Dillencourt [1987c] supports this thesis by proving a result concerning the connectivity of Delaunay triangulations.

A (euclidean) *traveling salesman tour* is a minimum-length cycle spanned by n

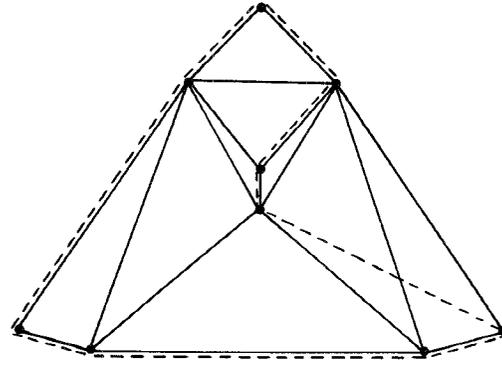


Figure 28. Delaunay triangulation and salesman tour [Dillencourt 1987].

sites. Constructing traveling salesman tours is a prominent problem of combinatorial optimization. Papadimitriou [1977] showed its NP-completeness. The problem becomes tractable for tours being close to optimal. It follows from the above discussion that the Delaunay triangulation will not contain a traveling salesman tour, in general.¹⁰ See also Figure 28 where the triangulation and the tour are drawn solid and dashed, respectively. Rosenkrantz et al. [1977], however, observed that traversing the minimum spanning tree twice will produce a tour that is within a factor of 2 of the optimum: Since removing an edge from the traveling salesman tour leaves a spanning tree of the sites, this tour must be longer than the minimum spanning tree. Note that this approximation algorithm takes only $O(n \log n)$ time. By partitioning the minimum spanning tree into paths, then constructing a minimum-length matching of their endpoints, Christofides [1976] improved this to a factor of 1.5, with the expense of an $O(n^2 \sqrt{n} \log^4 n)$ construction time due

¹⁰ This is even true for special traveling salesman tours called *necklace tours* that are cycles realizable as the intersection graph of disks around the sites. Necklace tours can be found in polynomial time in case of their existence [Edelsbrunner et al. 1987].

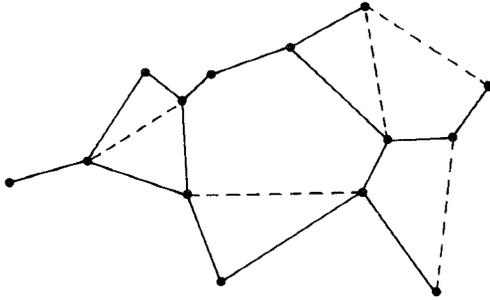


Figure 29. Relative neighborhood graph and Gabriel graph.

to the best known matching algorithm by Vaidya [1988b].¹¹

2.4.3 Relative Neighborhood and Gabriel Graph

It is worth mentioning two graphs that are “in between” the minimum spanning tree and the Delaunay triangulation in the sense of making explicit more proximity information than does the former and less than does the latter. Among them is the *relative neighborhood graph* that connects two sites provided no other site is closer to both of them than their interpoint distance. In Figure 29, the edges of the relative neighborhood graph are shown solid. Toussaint [1980] reported the usefulness of this structure in pattern recognition, and Supowit [1983] succeeded in constructing it in $O(n \log n)$ time, given the Delaunay triangulation. Yao (personal communication, 1988) announced that $O(n)$ time suffices for deriving the relative neighborhood graph from the latter. Interestingly, this graph retains its linear size in higher dimensions (provided a general placement of the sites). This stresses the importance of its rapid construction, especially in three dimensions, since it would imply fast minimum spanning tree algorithms. Un-

¹¹ A *minimum-length matching* of $2n$ sites is a graph with n edges joining pairs of sites, such that the pairs are distinct and the total edge length is minimized. Akl [1983] showed that a minimum-length matching is not necessarily a subgraph of the Delaunay triangulations of the sites.

fortunately, no algorithm with significantly subquadratic running time is known.

A similarly defined construct is the *Gabriel graph*. It contains an edge between two sites if the disk having that edge as its diameter is empty of sites. This concept proved useful in processing geographical data [Gabriel and Sokal 1969; Matula and Sokal 1980]. Howe [1978] observed that the Gabriel graph consists of just those Delaunay edges that intersect their dual Voronoi edges. Based on the same observation, Urquhart [1980] gave an $O(n \log n)$ time algorithm for its construction. It is easily seen that the Gabriel graph is a supergraph of the relative neighborhood graph. The edges of the former are shown solid or dashed in Figure 29.

2.5 Clustering Point Sites

Clustering a set of n point sites in the plane means determining partitions of the set that optimize some predefined clustering measure. This measure usually is a function of the interpoint distances of the set to be clustered.

2.5.1 Hierarchical Methods

A *single linkage clustering* [Hartigan 1975] hierarchically clusters the sites as follows. Initially, the sites are considered to be clusters themselves. As long as there is more than one cluster, the two closest clusters are merged. The distance of two clusters is defined as the minimum distance between any two sites, one from each cluster. This process can be carried out in a total of $O(n \log n)$ time by maintaining, at each stage, the following Voronoi diagram: Each point of the plane belongs to the region of the closest cluster, and closeness is with respect to the closest site within a cluster. The regions of the two closest clusters will always have a common edge in the diagram. That edge corresponds to an edge of the minimum spanning tree of the entire set of sites [Shamos and Hoey 1975].

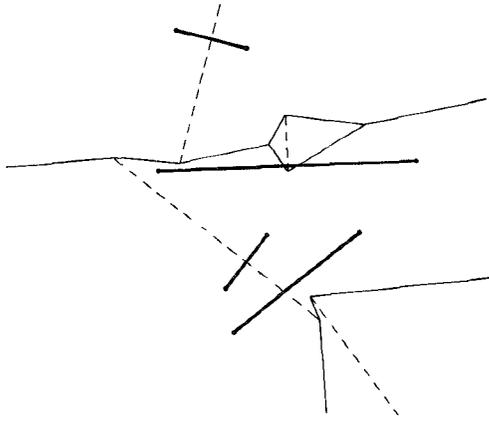


Figure 30. Complete linkage Voronoi diagram.

The model of *complete linkage clustering* is similar, except that the distance of two clusters is defined as the maximum distance between any pair of sites, one from each cluster. The corresponding Voronoi diagram, where closeness of a point in the plane is with respect to the furthest site in a cluster, deserves special attention. Its size is $\Omega(n^2)$ for general clusters and $O(n)$ provided the convex hulls of the clusters are pairwise disjoint [Edelsbrunner et al. 1989]. Figure 30 shows the diagram induced by four two-site clusters, indicated by bold segments. For each cluster, the portion of the bisector of its two sites that lies within its region is drawn dashed. The diagram can be constructed in $O(n \log n)$ randomized time for convex-hull disjoint and constant-sized clusters and—in this setting—applies to the retrieval of expected-nearest sites [Aurenhammer et al. 1991]. Efficient maintenance of the diagram during the clustering process would lead to an improved clustering algorithm but remains open.

2.5.2 Partitional Strategies

As another example, consider the problem of partitioning a set of n sites into a fixed number of t clusters such that the minimum of the (single linkage) distances between clusters is maximized. The following elegant $O(n \log n)$ -time so-

lution was proposed by Asano et al. [1988]. Construct the minimum spanning tree of the sites and remove its $t - 1$ longest edges. The resulting t subtrees already give the desired clustering. Using similar methods, Asano et al. [1988] obtain an equally efficient algorithm for partitioning the sites into two clusters so that their maximum diameter is minimized. This problem becomes considerably harder if partitions into more than two clusters are sought.¹² Partitions into *separable clusterings* have been investigated by Dehne and Noltemeier [1985] and Heusinger and Noltemeier [1989], who exploited the fact that clusters of k sites being separable from the remaining sites by a straight line define unbounded regions in the associated order- k Voronoi diagram.

2.5.3 Optimum Cluster Selection

The *k-variance problem* asks for selecting, from a given set S of n sites, a cluster of k sites with minimum variance, the sum of squares of all intersite distances in the cluster. Aggarwal et al. [1989b], who cite applications in pattern recognition, observed the following interesting fact. If C is k -cluster of minimal variance, then the region of C in the order- k Voronoi diagram of S is nonempty. Thus it suffices to examine the variances of sets of k sites associated with Voronoi regions. This can be done in time proportional to the number, $O(k(n - k))$, of regions by exploiting the fact that sets of neighbored regions differ in exactly two sites. Thus, the most time-consuming step is the precomputation of a higher order Voronoi diagram. A similar approach leads to improvements if the cluster measure to be minimized is not variance but diameter. If C is a k -cluster with minimum diameter, then C is contained in some set of $3k - 3$ sites whose region in the order- $(3k - 3)$ Voronoi diagram of S is nonempty;

¹² Asano et al. [1988] claimed its NP-completeness. Rote (personal communication, 1990), announced a polynomial algorithm in the case of three clusters.

see Aggarwal et al. [1989b] where an $O(k^2 n \sqrt{k} \log n)$ -time selection algorithm is obtained in this way.

Several other clustering algorithms that rely on Voronoi diagrams have been described in the literature; some of them are mentioned in the Introduction.

3. SELECTED TOPICS

A thorough understanding of the geometric, combinatorial, and topological properties of Voronoi diagrams is crucial for the design of efficient construction algorithms. This third part of the survey presents these properties in a unified manner and discusses their algorithmic implications. We start with a description of the various relationships of Voronoi diagrams to objects in one more dimension. We continue with some topological properties that are particularly useful for the divide-and-conquer construction of a large class of Voronoi diagrams in the plane. Finally, we investigate a continuous deformation of the planar Voronoi diagram being well suited to construction by the plane-sweep technique and extend it to generalized Voronoi diagrams.

3.1 Geometry of Voronoi Diagrams: Their Relationship to Higher Dimensional Objects

Voronoi diagrams are intimately related to several central structures in discrete geometry. This section exhibits these relationships in a comprehensive manner and discusses some of their geometric and algorithmic consequences. Although our main interest is in the classical type of Voronoi diagram, it is advantageous to base the discussion on the more general concept of power diagram since the geometric correspondences to be described extend to that type in a natural way. We shall refer to d dimensions in order to point out the general validity of the results.

3.1.1 Convex Polyhedral Surfaces

Consider a set S of n point sites in R^d such that each site $p \in S$ is assigned an

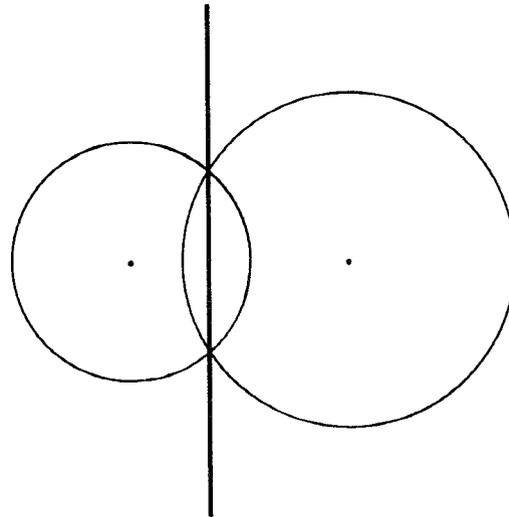


Figure 31. Power line of two circles.

individual real number $w(p)$ called its *weight*. The *power function* of a point $x \in R^d$ with respect to p is specified by

$$\text{pow}(x, p) = (x - p)^T(x - p) - w(p).$$

For $w(p) > 0$, one may think of the weighted site p as a sphere in R^d with radius $\sqrt{w(p)}$ around p ; for a point x outside this sphere, $\text{pow}(x, p) > 0$, and $\sqrt{\text{pow}(x, p)}$ expresses the distance of x to the touching point of a line tangent to the sphere and through x . In the plane, the locus of equal power with respect to two weighted sites p and q is commonly called the *power line* of the corresponding circles. If the circles are nondisjoint, their power line passes through their points of intersection; see Figure 31. In general dimensions, the locus of equal power is a hyperplane in R^d , called the *chordale* of p and q or $\text{chor}(p, q)$, for short. $\text{chor}(p, q)$ is orthogonal to the straight line connecting p and q but does not necessarily separate p from q . For $w(p) = w(q)$, $\text{chor}(p, q)$ degenerates to the symmetry hyperplane of p and q . Let $h(p, q)$ denote the closed halfspace bounded by $\text{chor}(p, q)$ and containing the

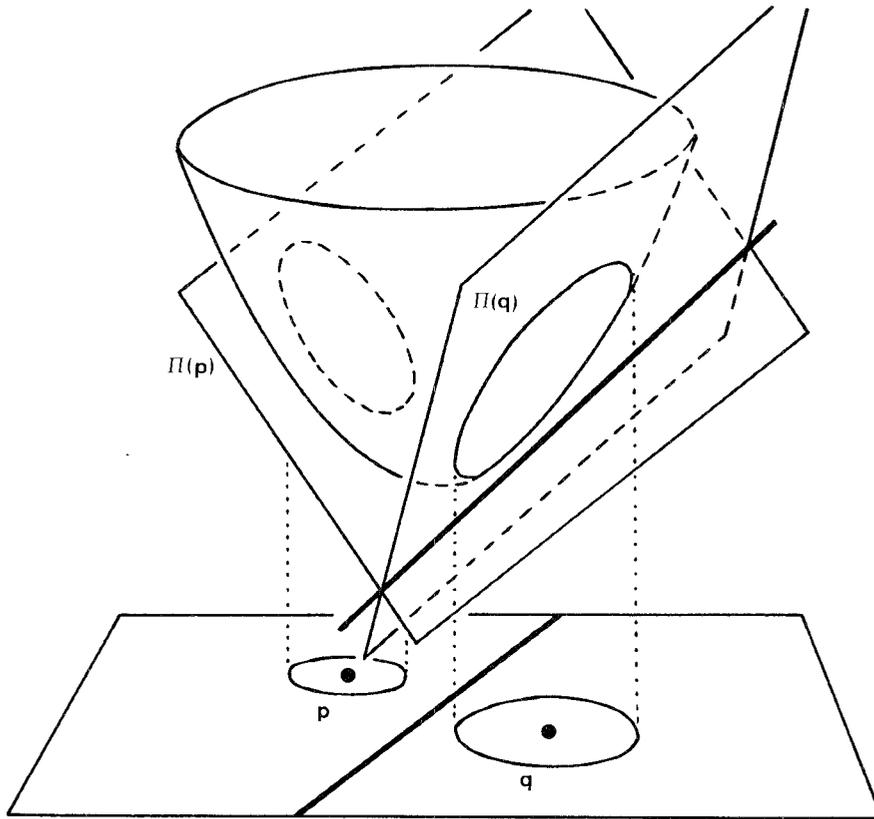


Figure 32. Spatial interpretation of chordale [Aurenhammer 1987a].

points of less power with respect to p . The power cell of p is given by

$$cell(p) = \bigcap_{q \in S - \{p\}} h(p, q).$$

In analogy to classical Voronoi regions, the power diagram of S , $PD(S)$ is the convex polyhedral complex defined in R^d by these cells; see Figure 4 for the case $d = 2$. $PD(S)$ coincides with the classical Voronoi diagram of S in the case of equally weighted sites. Note that power cells may be empty if general weights are used.

For technical reasons let us identify R^d with the linear subspace of R^{d+1} orthogonal to the $(d + 1)^{st}$ coordinate axis x_{d+1} . The key observation for the existence of objects in R^{d+1} that are related to power diagrams is that the power function $pow(x, p)$ can be expressed by

the hyperplane

$$\pi(p) : x_{d+1} = 2x^T p - p^T p + w(p)$$

in R^{d+1} [Aurenhammer 1987a]. This fact is best explained by reference to Figure 32. Let p and q be two sites in R^2 whose weights are indicated by circles. Projecting the circles onto the paraboloid of revolution $x_3 = x_1^2 + x_2^2$ defines two planes $\pi(p)$ and $\pi(q)$ that intersect the paraboloid in these projections. It is an easy analytical exercise to prove that the line $\pi(p) \cap \pi(q)$ projects orthogonally to the chordale $chor(p, q)$ in the $x_1 x_2$ -plane. This correspondence holds for arbitrary dimensions. As an immediate consequence, $PD(S)$ is the orthogonal projection of the boundary of the polyhedron that comes from intersecting the half-spaces of R^{d+1} above $\pi(p)$, for all $p \in S$. In fact, π is a bijective mapping between

weighted sites in R^d and hyperplanes in R^{d+1} . Thus, for any intersection of upper half-spaces there exists a corresponding power diagram in one dimension lower and vice versa.

This general result has far-reaching implications. Most important, it shows that power diagrams are in a geometric and combinatorial sense equivalent to unbounded convex polyhedra or, more precisely, to their boundaries, that is, to *convex polyhedral surfaces*. Convex polyhedra are well-understood objects in discrete geometry, hence so are power diagrams. Exact upper and lower bounds on the numbers of their faces of various dimensions are known. In particular, $PD(S)$ in R^d realizes at most n cells, f_j j -dimensional faces ($1 \leq j \leq d-1$), and $f_0 - 1$ vertices, for

$$f_j = \sum_{i=0}^a \binom{i}{j} \binom{n-d+i-2}{i} + \sum_{i=0}^b \binom{d-i+1}{j} \binom{n-d+i-2}{i},$$

$$a = \left\lfloor \frac{d}{2} \right\rfloor, b = \left\lfloor \frac{d}{2} \right\rfloor.$$

This follows from the so-called upper bound theorem [Brøndsted 1983]. The numbers f_j are $O(n^{\lceil d/2 \rceil})$ for $0 \leq j \leq d-1$.

As for the facets of a convex polyhedron, the power cells are convex but possibly unbounded polyhedra. Not every half-space within a given set needs to contribute to a facet, so power cells may be empty or degenerate. $d+1$ or more hyperplanes in R^{d+1} intersect in a common point (unless parallelism occurs), so at least $d+1$ power cells meet at each vertex of $PD(S)$. In particular, there are no vertices if the cardinality n of S does not exceed d . These and many other properties of $PD(S)$ can be read off conveniently from its $(d+1)$ -dimensional embedding.

3.1.2 Hyperplane Arrangements

In order to exploit the situation fully, we turn our attention to diagrams of higher order [Edelsbrunner 1987];

Aurenhammer [1987a]. To this end, the concept of a power cell is generalized to more than one site. Let T be a subset of k sites in S . The power cell of T is defined as

$$\text{cell}(T) = \bigcap_{p \in T, q \in S-T} h(p, q).$$

The complex of all (nonempty) power cells arising from the $\binom{n}{k}$ subsets of S with fixed cardinality k is known as the *order- k power diagram* of S , k - $PD(S)$. Clearly 1 - $PD(S) = PD(S)$ holds. Note that k - $PD(S)$ is just the order- k Voronoi diagram of S provided all sites in S are equally weighted. $(n-1)$ - $PD(S)$ is also called the *furthest site* power diagram of S .

Now let Z denote the intersection of the half-spaces below the hyperplanes $\pi(p)$ for all $p \in T$ and above the hyperplanes $\pi(q)$ for all $q \in S-T$. Due to the foregoing reasoning, Z projects orthogonally onto $\text{cell}(T)$ in R^d . This observation draws the connection between order- k power diagrams and so-called *hyperplane arrangements*. The latter are cell complexes that arise from dissecting the space by a finite number of hyperplanes. Each cell in an arrangement is the intersection of some half-spaces below or above its defining n hyperplanes. If we let a k -level consist of all cells lying below k and above $n-k$ hyperplanes, we can conclude that the k -level induced by $\{\pi(p) \mid p \in S\}$ projects to the cells of k - $PD(S)$ for each k between 1 and $n-1$. This shows that each arrangement in R^{d+1} corresponds to a complete family of higher order power diagrams in R^d and vice versa. The correspondence between order-1 power diagrams and convex polyhedral surfaces discussed earlier is a special case of this situation.

Figure 33 depicts a cell (left) being the intersection of five upper and three lower half-spaces, that is, a three-level cell. Its orthogonal projection onto the $x_1 x_2$ -plane is an order-3 power cell among eight sites (right) whose boundary is indicated by bold lines. Note that the power cell is

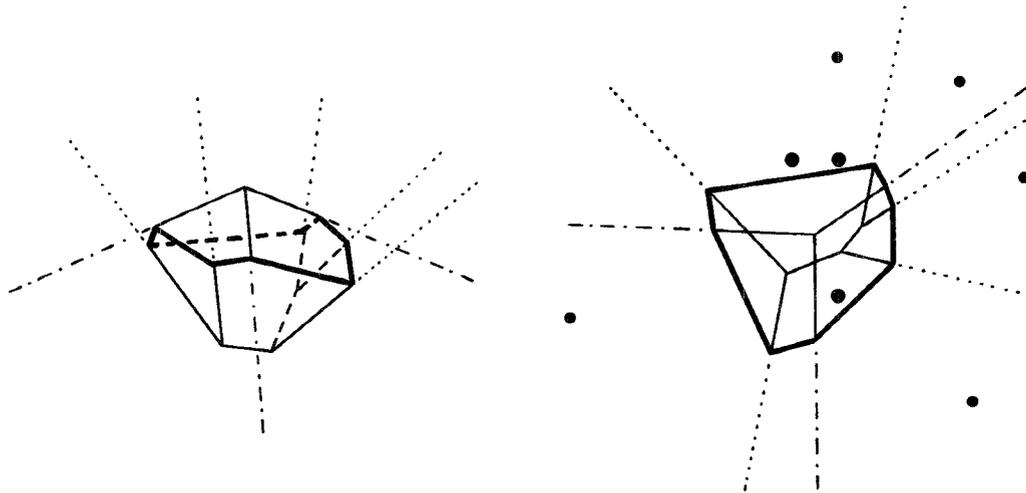


Figure 33. Projecting an arrangement cell [Aurenhammer 1987a].

carved into subcells by the furthest site power diagram of the three emphasized sites and by the power diagram of the remaining five sites.

The correspondence to arrangements straightforwardly yields an upper bound on the overall size of all higher order power diagrams of a fixed set of n sites: the maximal number of faces of an arrangement of n hyperplanes in R^{d+1} . This number is precisely

$$\sum_{i=d-j+1}^{d+1} \binom{i}{d-j+1} \binom{n}{i}$$

for faces of dimension j , which is in $O(n^{d+1})$ for $0 \leq j \leq d + 1$ [Alexanderson and Wetzel 1978]. Edelsbrunner et al. [1986a] developed an algorithm for constructing such arrangements in $O(n^{d+1})$ time. Consequently, the complete family of higher order power (or Voronoi) diagrams of a given set of sites can be computed in optimal time and space. Edelsbrunner [1986] showed how to construct the k -level of an arrangement in R^3 , and thus a single order- k power (or Voronoi) diagram in the plane, at a cost of $O(\sqrt{n} \log n)$ per edge. Recently, Mulmuley [1991] proposed a randomized algorithm for constructing levels of order 1 to k in $d \geq 4$ dimensions in worst-case optimal time.

We state another interesting consequence. Let $\pi'(p)$ denote the image of reflection of the hyperplane $\pi(p)$ through R^d . The cells in the k -level of $\{\pi'(p) \mid p \in S\}$ correspond bijectively to the cells in the $(n - k)$ -level of $\{\pi(p) \mid p \in S\}$ by reversing “upper” and “lower” for their supporting half-spaces. Clearly, any two corresponding cells yield the same orthogonal projection onto R^d . That is to say, they yield the same power cell that is simultaneously of order- k and order- $(n - k)$ for fixed k . This shows that any order- k power diagram for n sites can be interpreted as some order- $(n - k)$ power diagram. In particular, the furthest site power diagram of S is the order-1 power diagram of some set of sites (distinct from S , in general). We point out that this is not true for the subclass of classical Voronoi diagrams, as can be seen from the maximal size of their closest site and furthest site counterparts that differ even in R^2 ; see the Introduction and Section 2.2.1.

Finally, let us mention a result on power cells in R^2 . Let $T \subset S$ and $|T| = k$. By definition, $\text{cell}(T)$ is the intersection of $k(n - k)$ half planes and thus might have that many edges. On the other hand, $\text{cell}(T)$ is the projection of a polyhedron in R^3 that has at most n facets and thus only $O(n)$ edges by

Euler's relation. It follows that $\text{cell}(T)$ has $O(n)$ edges and can be constructed in $O(n \log n)$ time by intersecting n half-spaces of R^3 .

3.1.3 Convex Hulls

The *convex hull* of a finite point set is the intersection of all half-spaces containing this set. Next, we study the duality of (order-1) power diagrams and convex hulls [Aurenhammer 1987a]. Duality is usually defined for convex polyhedra. Let Z and Z' be two convex polyhedra in R^{d+1} . Z and Z' are said to be *dual* if there is a bijective mapping ψ between the j -dimensional faces of Z and the $(d-j)$ -dimensional faces of Z' such that $f \subseteq g$, for any two faces f and g of Z if and only if $\psi(g) \subseteq \psi(f)$. Since power diagrams in R^d are projections of convex polyhedral surfaces in R^{d+1} , the notion of duality carries over in a natural manner.

We now consider, for each site $p \in S$ with weight $w(p)$, a point in R^{d+1} :

$$\Delta(p) = \begin{pmatrix} p \\ p^T p - w(p) \end{pmatrix}.$$

From the formula expressing the hyperplane $\pi(p)$ it can be seen that $\Delta(p)$ and $\pi(p)$ are related via *polarity* with respect to the paraboloid of revolution. $\Delta(p)$ is the *pole* of $\pi(p)$ and $\pi(p)$ is the *polar hyperplane* of $\Delta(p)$. If $\pi(p)$ happens to intersect the paraboloid, then polarity has the geometric interpretation displayed in Figure 34. The hyperplanes touching the paraboloid at its points of intersection with $\pi(p)$ all concur at $\Delta(p)$.

Recall that the intersection, Z , of the half-spaces above $\pi(p)$, for all $p \in S$, projects to $PD(S)$. Take an arbitrary j -dimensional face of Z that lies in the intersection of, say, $\pi(p_1), \dots, \pi(p_m)$, $m \geq d-j+1$. That is, there exists some point on these but below all other hyperplanes defined by S . Since polarity preserves the relative position between points and hyperplanes, there is a hyperplane with $\Delta(p_1), \dots, \Delta(p_m)$ on it and $\Delta(q)$ above it, for all remaining sites

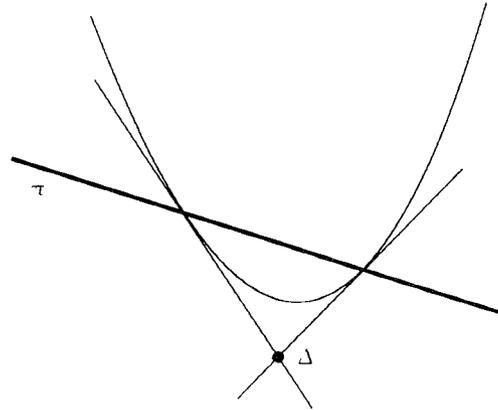


Figure 34. Polarity between points and lines.

$q \in S$. This, however, means that $\Delta(p_1), \dots, \Delta(p_m)$ span a $(d-j)$ -dimensional face of the *lower part* of the convex hull of the point-set $\{\Delta(p) \mid p \in S\}$. This lower part consists of all boundary faces of the hull that are visible from the point on the x_{d+1} -axis at $-\infty$. In other words, we have shown the duality of Z , and thus of $PD(S)$, to that lower convex hull part.

By the same reasoning, the duality of the furthest site power diagram of S and the *upper part* of the convex hull of $\{\Delta(p) \mid p \in S\}$ can be established. This reveals another interesting link between closest site and furthest site power diagrams and, particularly, classical Voronoi diagrams. Most important, these diagrams become constructable in general dimensions d via convex-hull algorithms. Running times of $O(n \log n)$ for $d=2$ and of $O(n^{\lceil d/2 \rceil})$ for odd d are achieved, both of which are worst-case optimal; see Preparata and Hong [1977] and Seidel [1981], respectively. For even $d \geq 4$, these diagrams can be computed at logarithmic time per face [Seidel 1986].

By projecting down the edges of the lower and upper part of the convex hull that arises from a Voronoi diagram, one obtains the closest site and furthest site Delaunay triangulation, respectively. In such a triangulation, each edge is orthogonal to its dual facet. Conversely, the existence of some set of sites allowing a

triangulation whose edges are orthogonal to the facets of a given cell complex in R^d is a necessary and sufficient condition for that cell complex to be a power diagram or, equivalently, to be the projection of a convex polyhedral surface [Aurenhammer 1987b, 1987c]. If the given cell complex is *simple* (i.e., exactly $d + 1$ cells meet at each vertex), a projection surface can be reconstructed, if it exists, in time proportional to the number of facets of that cell complex. It is well known that such a surface always exists except for $d = 2$. This implies that any simple complex of n cells in $d \geq 3$ dimensions, which might have a large number of lower dimensional faces, can be specified by storing only n half-spaces of R^{d+1} .

Surprisingly, even higher order power diagrams are dual to some convex hull in R^{d+1} [Aurenhammer 1990a]. For any subset T of S with k sites let $\Delta(T)$ denote the point in R^{d+1} whose orthogonal projection onto R^d and whose $(d + 1)^{st}$ coordinate are

$$\sum_{p \in T} p \quad \text{and} \quad \sum_{p \in T} [p^T p - w(p)],$$

respectively. This definition conforms to the case $k = 1$ since $\Delta(T) = \Delta(p)$ when $T = \{p\}$. Using arguments similar as for $k = 1$, one may verify that the lower part of the convex hull of the point-set

$$S_k = \{\Delta(T) \mid T \subset S, |T| = k\}$$

is dual to k -PD(S). As one corollary, that very lower part has to be dual to the intersection of some corresponding upper half-spaces and hence to an order-1 power diagram. To be more precise, k -PD(S) coincides with PD(S'_k), for S'_k being the (accordingly weighted) orthogonal projection of S_k onto R^d . This implies that the class of power diagrams is closed under order- k modification—another result that is not true for the more restrictive class of classical Voronoi diagrams. From the algorithmic viewpoint, k -PD(S) becomes constructable via convex hull algo-

rithms. For example, the planar Voronoi diagram of order- k can be obtained from its order- $(k - 1)$ predecessor in $O(kn \log n)$ time by simply computing a convex hull in R^3 . Insertions and deletions of sites in an order- k Voronoi diagram also amount to computing certain convex hulls; these operations even can be handled on-line in an efficient manner [Aurenhammer and Schwarzkopf 1991].

3.1.4 k -Sets

Let Q be a set of n points in R^{d+1} . A k -set of Q is a subset of k points of Q that can be separated from the remaining $n - k$ points by some hyperplane of R^{d+1} . The discussion in the foregoing section reveals a correspondence between k -sets and order- k power diagrams.

By polarity, points in Q can be transformed into hyperplanes; each point $q \in Q$ bijectively corresponds to a weighted site p in R^d such that $\Delta(p) = q$ and thus to the hyperplane $\pi(p)$ in R^{d+1} . Now, let M be a k -set of Q , and consider a hyperplane h that separates M from $Q - M$. Without loss of generality, M lies below h . Equivalently, the pole of h lies below all polar hyperplanes of the points in M and above all polar hyperplanes of the points in $Q - M$. Hence the intersection of the corresponding lower and upper half-spaces of R^{d+1} bounded by these polar hyperplanes is nonempty. This intersection, being a cell in the k -level of a hyperplane arrangement, projects to a cell of the order- k power diagram of a set of weighted sites, $\{p \in R^d \mid \Delta(p) \in Q\}$.

We have obtained a one-to-one correspondence between k -sets in R^{d+1} and power cells in R^d . This allows us to apply known results on the number of k -sets to the analysis of the size of order- k power diagrams. Let $f_d(k, n)$ denote the maximum number of k -sets of any set of n points in R^d . Known asymptotic values of this function are $f_2(k, n) = \Omega(n \log k)$ and $f_2(k, n) = O(n\sqrt{k})$ [Edelsbrunner and Welzl 1985], $f_3(k, n) = \Omega(nk \log k)$ and $f_3(k, n) = O(n^{8/3} \log^{5/3} n)$ [Edelsbrunner et al. 1986; Aronov et al. 1990, respectively]. Not surprisingly, a

better understood quantity is

$$g_d(k, n) = \sum_{j=1}^k f_d(j, n).$$

Chazelle and Preparata [1986] showed $g_3(k, n) = O(nk^5)$ and Clarkson [1987] showed $g_3(k, n) = O(n^{1+\epsilon}k^2)$, for any $\epsilon > 0$. Note that $g_d(n-1, n) = O(n^d)$ according to the maximum number of cells of a hyperplane arrangement in R^d . Recently, Clarkson and Schor [1989] succeeded in proving $g_d(k, n) = \Theta(n^{\lfloor d/2 \rfloor} k^{\lceil d/2 \rceil})$ as $n/k \rightarrow \infty$ for fixed d . Determining exact or at least asymptotically tight bounds on $f_d(k, n)$ still remains an important open problem.

3.1.5 Related Diagrams

The central role of power diagrams within the context of Voronoi diagrams becomes even more apparent by the observations described below [Aurenhammer and Imai 1988]. Let p , q , and r denote three weighted sites. For the three chordales they define, $\text{chor}(p, q) \cap \text{chor}(q, r) \subset \text{chor}(p, r)$ necessarily holds. It is not difficult to see that this condition is also sufficient for three hyperplanes to be the chordales defined by three sites if we keep in mind the relationship between chordales in R^d and intersections of hyperplanes in R^{d+1} . On the other hand, the condition is trivially fulfilled by the separators for any Voronoi diagram with polyhedral regions since the regions would not form a cell complex otherwise. We thus conclude that any Voronoi diagram whose separators are hyperplanes is a power diagram. This result applies to diagrams defined by the *general quadratic-form distance*

$$Q(x, p) = (x - p)^T M(x - p) - w(p),$$

with M a nonsingular and symmetric ($d \times d$)-matrix and thus to many particular distance functions considered in the literature. Note that Q equals the power function if M is the identity matrix.

One is tempted to believe that power diagrams are related solely to objects in

higher dimensions. Below we will show that a certain rather general type of Voronoi diagram in R^{d-1} can be embedded into a power diagram in R^d . To this end, we identify R^{d-1} with the linear subspace $x_d = 0$ of R^d . Let p be some point site in R^{d-1} and consider an arbitrary distance function $f(x, p)$ for p . For some strictly increasing function F on R , we define the *cone* of p with respect to F as

$$\begin{aligned} \text{cone}_F(p) &= \left\{ \begin{pmatrix} x \\ x_d \end{pmatrix} \mid x \in R^{d-1}, x_d = F(f(x, p)) \right\}. \end{aligned}$$

A Voronoi diagram for point sites in R^{d-1} under the distance function f is termed *transformable* if there exists an F that forces the affine hull, $\alpha(p, q)$, of $\text{cone}_F(p) \cap \text{cone}_F(q)$ to be a hyperplane in R^d for any distinct sites p and q . Transformable diagrams represent projected sections of power diagrams in R^d . A point $x \in R^{d-1}$ satisfies $f(x, p) < f(x, q)$ if and only if its projection, x' , onto $\text{cone}_F(p)$ lies in a fixed (open) half-space, $h(p, q)$, bounded by $\alpha(p, q)$. As a consequence, x belongs to p 's region exactly if

$$x' \in Z = \bigcap_{q \in S - \{p\}} h(p, q),$$

for S being the underlying set of sites in R^{d-1} . But the d -dimensional polyhedron Z is a power cell since $\alpha(p, q) \cap \alpha(q, r) \subset \alpha(p, r)$ holds so that these affine hulls can be interpreted as chordales. In conclusion, the boundary of p 's region is the orthogonal projection onto R^{d-1} of $\text{cone}_F(p)$ intersected with a power cell in R^d .

Transformable Voronoi diagrams occur for the *additively weighted distance*,

$$a(x, p) = \delta(x, p) - w(p)$$

$$\text{with } F(a) = a,$$

and the *multiplicatively weighted distance*,

$$m(x, p) = \frac{\delta(x, p)}{w(p)} \quad \text{with } F(m) = 2m^2.$$

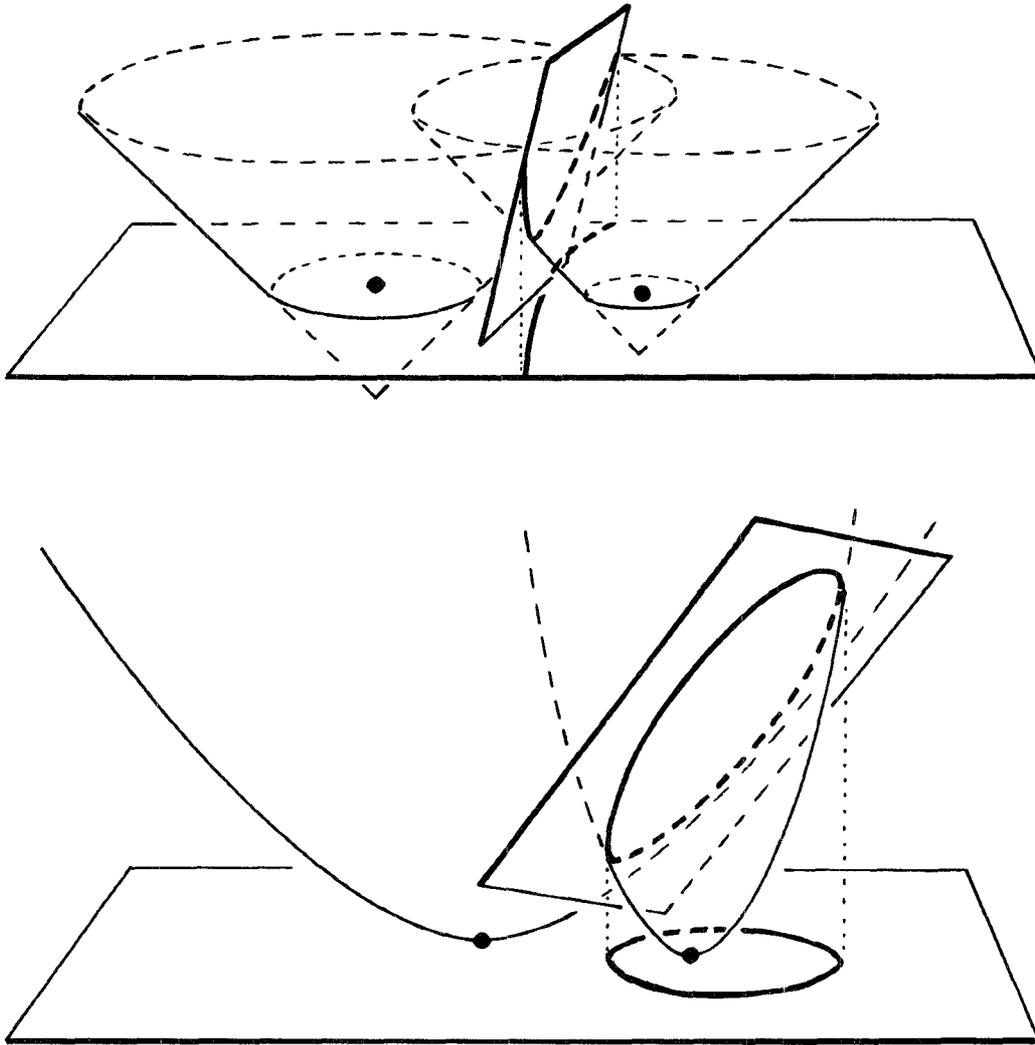


Figure 35. Cones for two distance functions.

The former gives rise to hyperbolically bounded and star-shaped regions (the Johnson-Mehl model, Figure 6), whereas the latter induces spherically bounded regions (the Apollonius model, Figure 12). Its regions are disconnected, in general, which already reflects the major complexity of the latter type.

Figure 35 displays cones for the additively weighted distance (above) and the multiplicatively weighted distance (below). They are cones of revolution in the former case—intersecting in a hyperbola that projects down to a hyperbolic

separator—and paraboloids of revolution in the latter case—intersecting in an ellipsis that projects down to a circular separator. In both cases, the affine hull of cone intersections is a plane.

Upper bounds on the size of both types of diagram in d dimensions can be derived from the maximum size of a power diagram in R^{d+1} . Concerning the algorithmic aspects of this relationship, the only known algorithms for constructing these diagrams in $d \geq 3$ dimensions are obtained. The Apollonius model in the plane can be computed in $O(n^2)$ time and

space, which is worst-case optimal. We mention that the notion of embeddability generalizes nicely to order k .

3.1.6 Upper Envelopes

Let f_1, \dots, f_t be piecewise linear d -variate functions on R^d . In the following, we will not distinguish between a function on R^d and its graph in R^{d+1} . Consider the pointwise maximum, U , of these functions:

$$U(x) = \max_{1 \leq i \leq t} f_i(x).$$

U is called the *upper envelope* of f_1, \dots, f_t . We have already observed that certain upper envelopes are related to power diagrams. For any set S of weighted sites in R^d , the upper envelope of the hyperplanes $\pi(p)$, $p \in S$, projects to $PD(S)$. Below we briefly consider two types of Voronoi diagrams where this relationship generalizes particularly well.

Let S be a set of n point sites in the plane, and consider a partition of S into subsets C_1, \dots, C_t called *clusters*. The *Hausdorff distance* of a point x to the cluster C_i is defined as

$$h(x, C_i) = \max\{\delta(x, p) \mid p \in C_i\}.$$

h is also called the complete linkage distance; compare Section 2.5.1. Each cluster C_i may be associated with a convex polyhedral surface $\text{cap}(C_i)$ in R^3 , being the boundary of the polyhedron that comes from intersecting the half-spaces below $\pi(p)$ for all $p \in C_i$. Easy arguments show the following. For any point x in the plane, $h(x, C_i) < h(x, C_j)$ if and only if the vertical line through x intersects $\text{cap}(C_i)$ in a point lying above $\text{cap}(C_j)$. This implies that the upper envelope of $\text{cap}(C_1), \dots, \text{cap}(C_t)$ projects to the Voronoi diagram induced by C_1, \dots, C_t and h . For an illustration of the Voronoi diagram for two-site clusters see Figure 30.¹³

To obtain another example, assume that visibility of the sites is constrained

¹³ Observe that the upper envelope of $\text{cap}(T)$, for all subsets T of k sites of S , consists of faces of the k -level of $\{\pi(p) \mid p \in S\}$ and thus projects to the order- k Voronoi diagram of S .

to a *window*, W , a segment on a line avoiding the convex hull of S . A site $p \in S$ and a point x are called *visible* if the line segment joining x and p intersects W . The *peeper's Voronoi diagram* of S and W assigns each point in the plane to the region of the closest site visible from it. See Figure 36 where the window is shown between two bold line segments. The diagram is composed of perpendicular bisectors of sites (dashed) and of rays through sites and window endpoints (solid).

Each site p may be associated with an unbounded convex polygon $\text{plate}(p)$ in R^3 , being the projection onto $\pi(p)$ of the set of all points visible from p . Again it is easy to see that a point x falls into the region of a site p just if the vertical line through x intersects $\text{plate}(p)$ in a point that lies above $\text{plate}(q)$ for all $q \in S - \{p\}$. We conclude that the upper envelope of $\text{plate}(p)$, $p \in S$, projects to the peeper's Voronoi diagram of S .

Upper envelopes of piecewise linear functions on R^2 are well-studied geometric objects. Pach and Sharir [1989] showed that they can attain a size of $\Theta(n^2\alpha(n))$, where n is the total number of triangles needed in partitioning the linear pieces of these functions and where α denotes the inverse of Ackermann's function. Construction algorithms exist that run in time proportional to their worst-case size; see Edelsbrunner et al. [1989] who also give a lower bound of $\Omega(n^2)$ on the size of a cluster Voronoi diagram. Recent results on upper envelopes by Huttenlocher et al. [1991] imply that the diagram for t clusters with a total of n sites has a size of $O(tn\alpha(tn))$. The upper envelope arising from the peeper's Voronoi diagram has a worst case size of $\Theta(n^2)$ [Aurenhammer and Stöckl 1988]. Note that the superlinear size of a diagram implies the existence of disconnected regions.

3.2 Topology of Planar Diagrams: Divide-and-Conquer Construction and Its Variants

By far not all types of Voronoi diagrams considered in the literature can be

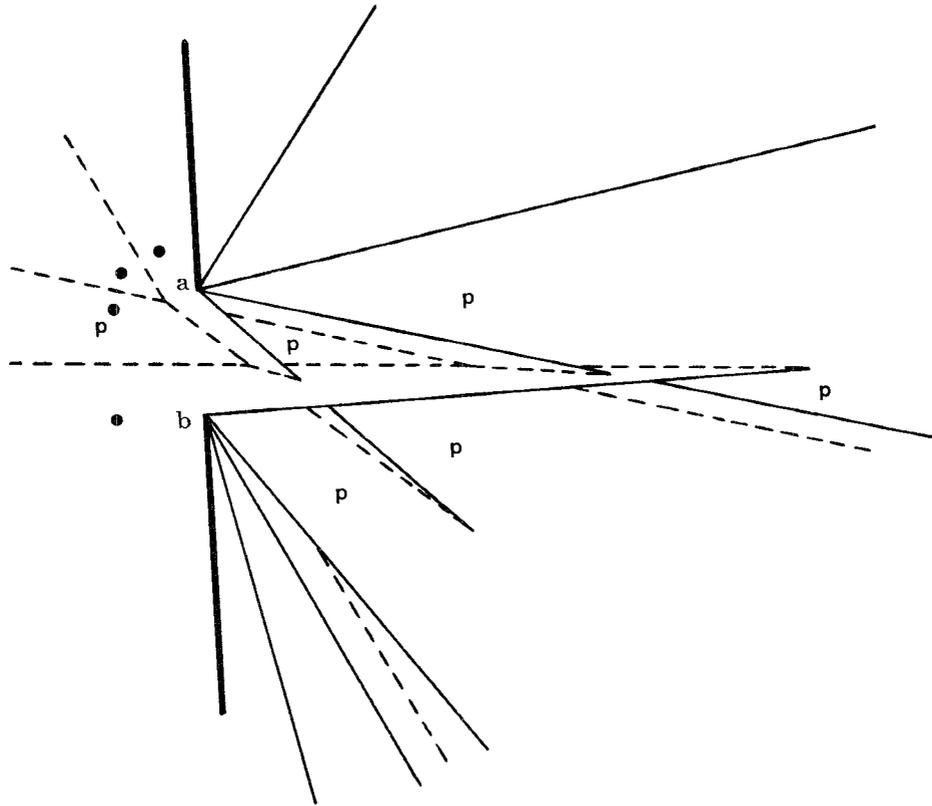


Figure 36. Peeper's Voronoi diagram.

brought into connection with geometric objects having nice algorithmic properties, like convex hulls or hyperplane arrangements. So there is need for finding features common to such “ungeometric” diagrams. We do this by extracting topological properties, being guided by their relevance to the divide-and-conquer construction of Voronoi diagrams. Attention is restricted to the plane as the instance of most applications and easiest analysis.

The concept of diagram we are interested in here may be characterized as follows. The n sites are points in R^2 . The distance function varies by different shapes of its “circles” that may depend on local properties of R^2 . It thus may vary for the individual sites.

3.2.1 Convex Distance Functions

An important type fitting into the concept above is generated by the convex

distance function or the Minkowski distance [Chew and Drysdale 1985]. Let C denote the boundary of some compact and convex subset of R^2 with the origin o in its interior. The distance with respect to C of o to some point $x \in R^2$ is given by

$$d_C(x, o) = \frac{\delta(x, o)}{\delta(x', o)}$$

for x' being the point of intersection of C and the ray from o to x . Clearly d_C can be defined with respect to any site q of a given set S by translating C so that q occupies the former position of o . Observe that $d_C(x, q)$ depends on the euclidean distance $\delta(x, q)$ as well as on the direction of the ray from q to x . Convex distance functions include, among others, the general L_p -metric

$$\delta_p(x, q) = \sqrt[p]{|q_1 - x_1|^p + |q_2 - x_2|^p},$$

with

$$q = \begin{pmatrix} q_1 \\ q_2 \end{pmatrix} \quad \text{and} \quad x = \begin{pmatrix} x_1 \\ x_2 \end{pmatrix},$$

whose most important instances are for $p = 1$ (the *Manhattan metric*; C is a square rotated by 45°), $p = 2$ (the *euclidean distance*; C is a circle), and $p = \infty$ (the *Maximum metric*; C is an axis-parallel square). Note that d_C is a metric only if C is point-symmetric with respect to q since $d_C(q, r)$ might differ from $d_C(r, q)$ otherwise. However, the triangle inequality

$$d_C(q, r) + d_C(r, s) \geq d_C(q, s)$$

can easily be shown to hold even if C is not point-symmetric.

Let us now investigate the Voronoi diagram defined by d_C and a set S of n sites in R^2 . From the classical type we adopt the notions of separator $\text{sep}(q, r)$ of q and r , dominance $\text{dom}(q, r)$ of q over r , and region $\text{reg}(q)$ of q ; compare the Introduction. Clearly $\text{sep}(q, r)$ need not be a straight line as is the case for euclidean distance. An even more unpleasant phenomenon is that $\text{sep}(q, r)$ fails to be one dimensional in general. To remedy this shortcoming, the notions above may be redefined slightly by referring to the lexicographical order (symbolized by $<$) of the sites in S [Klein and Wood 1988]. The dominance of q over r is redefined as

$$\text{Dom}(q, r) = \begin{cases} \text{dom}(q, r) - \text{sep}(q, r), & \text{if } q < r \\ \text{dom}(q, r), & \text{otherwise.} \end{cases}$$

The new separator, $\text{Sep}(q, r)$, is the intersection of the boundaries of $\text{Dom}(q, r)$ and $\text{Dom}(r, q)$, which is obviously one-dimensional. Figure 37 shows a two-dimensional separator in the L_1 -metric (left) and its redefined version (right). For a Voronoi diagram in the L_1 -metric, see Figure 3. The region of a site q now can be rewritten as

$$\text{Reg}(q) = \bigcap_{r \in S - \{q\}} \text{Dom}(q, r).$$

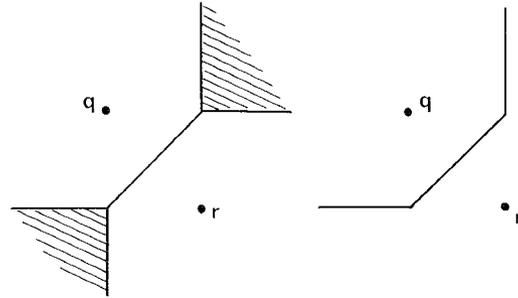


Figure 37. Redefining a separator.

That is, each point in R^2 belongs to the region of the lexicographically least site among its closest sites in S . This ensures that the interiors of the regions cover the plane up to a set of Lebesgue measure zero.

Defined in this way, the Voronoi diagram, $V_C(S)$, for a convex distance function d_C has the nice property that its regions are *star shaped*; $\text{Reg}(q)$ contains the straight-line segment between q and x for each $x \in \text{Reg}(q)$. To prove this by contradiction, assume the existence of a point y on this segment with $d_C(y, q) > d_C(q, r)$, for $r \in S - \{q\}$. This implies $d_C(x, q) = d_C(x, y) + d_C(y, q) > d_C(x, y) + d_C(y, r)$. By the triangle inequality, the latter sum is greater than or equal to $d_C(x, r)$ so that $d_C(x, q) > d_C(x, r)$, that is, $x \notin \text{Reg}(q)$, follows.

The star shapedness of the regions implies their simple connectedness. Clearly, regions cannot vanish since $q \in \text{Reg}(q)$ holds for all $q \in S$. So $V_C(S)$ can be viewed as a planar graph with exactly n regions. Since vertex degrees are at least three, there are $O(n)$ edges and vertices. We conclude a linear bound on the size of $V_C(S)$.

3.2.2 Divide-and-Conquer Construction

Our next aim is to show that Voronoi diagrams for convex distance functions can be constructed efficiently by a *divide-and-conquer* algorithm. Divide and conquer splits the problem at hand into two smaller subproblems, computes their solutions recursively (unless they

are very small and can be solved by trivial methods), and finally combines the partial solutions to the global one. The V_C type of diagram is well suited to attack by this strategy. The underlying set S of sites is partitioned into two subsets S_1 and S_2 of nearly equal cardinality. $V_C(S_1)$ and $V_C(S_2)$ are computed recursively and are then merged to $V_C(S)$.

The merge step deserves the main attention since it actually constructs the diagram. We will discuss this process in some detail and under the simplifying but computationally unrestrictive assumption that S_1 and S_2 are separable by a vertical line. Since $V_C(S_1)$ as well as $V_C(S_2)$ defines a partition of R^2 , any point $x \in R^2$ falls into the region $\text{Reg}_1(q)$ of $V_C(S_1)$ for some site $q \in S_1$ and into the region $\text{Reg}_2(r)$ of $V_C(S_2)$ for some site $r \in S_2$. Now observe that $x \in \text{Reg}(q)$ of $V_C(S)$ if $d_C(x, q) < d_C(x, r)$, and $x \in \text{Reg}(r)$ of $V_C(S)$ otherwise. So we have to cut off some part from $\text{Reg}_1(q)$ and from $\text{Reg}_2(r)$ by means of $\text{Sep}(q, r)$ in order to obtain $\text{Reg}(q)$ and $\text{Reg}(r)$. Carrying out this task for all relevant pairs of sites constitutes the merge process. The union of the newly integrated pieces of separators will be called the *merge chain*, $M(S_1, S_2)$.

The efficiency of an implementation of the merge process critically depends on the topological properties of the merge chain. We first show that $M(S_1, S_2)$ behaves well if the euclidean distance δ is taken for d_C [Shamos and Hoey 1975]. As a matter of fact, each horizontal line intersects $M(S_1, S_2)$ in exactly one point in this case, that is to say, $M(S_1, S_2)$ is (vertically) *monotone*. $M(S_1, S_2)$ is a polygonal line composed of edges of the classical diagram $V(S)$ that are portions of perpendicular bisectors of sites in S_1 and S_2 , respectively. Figure 17 gives an illustration. If there were a horizontal line intersecting the merge chain in two or more points, some site $q \in S_1$ would be forced to have a larger x_1 -coordinate than a site $r \in S_2$. This contradicts the assumption that S_1 and S_2 are separable by a vertical line; compare Figure 38.

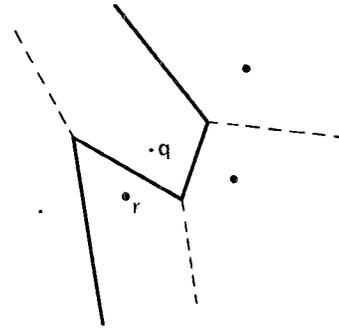


Figure 38. Impossible merge chain.

The monotonicity of $M(S_1, S_2)$ implies its connectedness and unboundedness. Hence the merge chain may be constructed edge by edge, starting with an unbounded one. As is mentioned in the Introduction, unbounded edges separate sites on the convex hull of S . So it suffices to determine a site in S_1 and a site in S_2 that are neighbors on the boundary of the convex hull of S . This can be accomplished in $O(n)$ time by finding a line tangent to the convex hulls of respective S_1 and S_2 . Each further edge of $M(S_1, S_2)$ is found by tracing the boundaries of the current regions of $V(S_1)$ and $V(S_2)$ in an appropriate direction until they intersect the actual separator. Easy counting arguments show that only $O(n)$ edges are processed in total: Each edge traced is either discarded or shortened to a new edge of $V(S)$. This implies an overall runtime of $O(n)$ for the merge process. By the recurrence relation $T(n) = 2T(n/2) + O(n)$ that results from using divide and conquer, the time complexity $T(n)$ for computing a classical Voronoi diagram is $O(n \log n)$.

Let us now come back to the distance d_C for general convex shapes C [Chew and Drysdale 1985]. As in the euclidean case, $M(S_1, S_2)$ is composed of those parts of the boundaries of regions of $V_C(S)$ that separate sites in S_1 from sites in S_2 . Thus $M(S_1, S_2)$ is one dimensional. Potentially, this merge chain may consist of cyclic and acyclic (but then necessarily unbounded) topological curves in R^2 .

Examples show that $M(S_1, S_2)$ is in fact disconnected in general. Its connected components all, however, are acyclic and thus unbounded. Let us prove that there are no cycles by assuming the existence of some cycle M and deducing a contradiction. Without loss of generality, M encircles a subset T of sites in S_1 . Clearly, then M does not encircle any site in S_2 . Furthermore, there exists a leftmost point $x \in M$ with $x \in \text{Sep}(r, s)$ for some $r, s \in S_2$. Since the regions of $V_C(S)$ are star shaped, the three open line segments from x to r , s , and some $q \in T$, respectively, do not intersect M . Thus, as r and s lie to the right of q , x has to lie to the left of q . This, however, contradicts the convexity of the underlying shape. C encircles x and passes through q , r , and s since the last three points are equidistant from x with respect to d_C . Figure 39 illustrates this situation; M and C are shown bold and dashed, respectively.

In order to construct the acyclic merge chain $M(S_1, S_2)$, one needs to detect some unbounded edge of each of its connected components. The previously described procedure of tracing boundaries of regions may then be applied. Unfortunately, the convex-hull method that works successfully in the euclidean case fails to be correct for d_C . To get an alternative method, we observe that each unbounded edge has to be contained in the intersection of two unbounded regions of $V_C(S_1)$ and $V_C(S_2)$, respectively. By a circular scan through these regions, each relevant pair $\text{Reg}_1(q)$ and $\text{Reg}_2(r)$ can be found and intersected with $\text{Sep}(q, r)$ in a total of $O(n)$ time. If $\text{Reg}_1(q) \cap \text{Reg}_2(r) \cap \text{Sep}(q, r)$ extends to infinity, then this edge is taken as the starting edge for a connected component of $M(S_1, S_2)$.

The linear-time behavior of the merge process thus can be maintained for general convex distance functions d_C . Consequently, $V_C(S)$ requires $O(n \log n)$ time and $O(n)$ space for construction. Of course, the complexity analysis is based on the assumption that d_C is *computationally simple*. That is, $d_C(q, x)$ can be calculated in $O(1)$ time for all $q \in S$ and

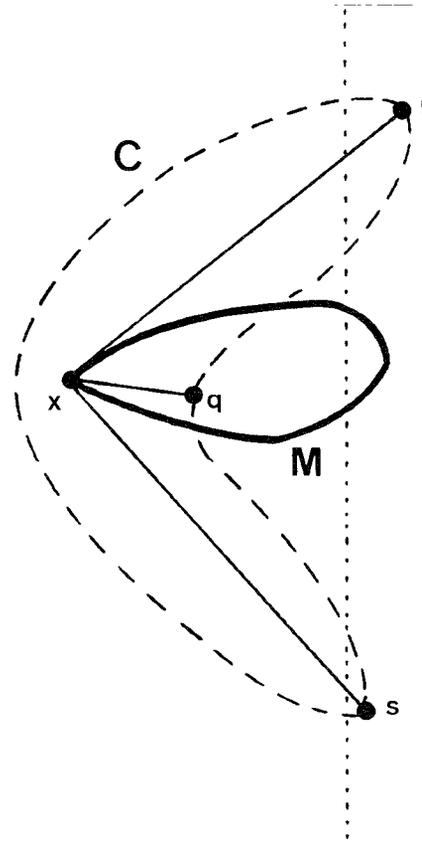


Figure 39. Cycles do not occur.

$x \in R^2$, and, in addition, its separators can be computed and intersected in $O(1)$ time. This may not be the case for complex shapes C , however.

3.2.3 Nice Metrics

We have seen that divide and conquer is a powerful approach to the construction of generalized Voronoi diagrams. It also applies well to sites more general than points; see Section 1.3.3. We do not pursue these modifications here, however, since they do not fit into the present concept of a diagram. Instead, we attempt to characterize metrics in R^2 that preserve the two main properties of a Voronoi diagram exploited in the preceding discussion [Klein 1989; Klein and Wood 1988]: the connectedness of regions

that implies an $O(n)$ size and the absence of cycles in the merge curve that allows an $O(n \log n)$ time construction.

Let d be any metric in R^2 that induces the euclidean topology. A curve γ in R^2 is termed *d-straight* if, for any three consecutive points x, y, z on γ , the equality

$$d(x, y) + d(y, z) = d(x, z)$$

holds. Clearly δ -straight curves are straight-line segments, for δ being the euclidean metric. By arguments similar to that used for convex distance functions (namely using the triangle inequality), it can be verified that any Voronoi region $\text{Reg}(p)$ for d is *d-star-shaped*: $\gamma \subset \text{Reg}(p)$ holds for the *d-straight* curve γ from p to any $x \in \text{Reg}(p)$. The *d-star-shapedness* of $\text{Reg}(p)$ does not necessarily imply its connectedness since *d-straight* curves do not always exist. If, however, for any two points $x, z \in R^2$ there is some y distinct from x, z with $d(x, y) + d(y, z) = d(x, z)$, then the existence of γ is guaranteed. Hence the Voronoi regions under those metrics are connected.

Posing an additional restriction on the metric d makes the Voronoi diagram even more well behaved: Assume that, for any point $m \in R^2$ and for any positive number r , the generalized disk

$$D = \{x \in R^2 \mid d(x, m) \leq r\}$$

with center m and radius r under the metric d is a simply connected set. For fixed r , the shape of D may vary with the position of m provided D remains simply connected. *Symmetric* convex distance functions d_C (i.e., with point-symmetric shape C) constitute a special case of translation-invariant disks. And, indeed, the proof that merge chains are acyclic can be extended from convex distance functions to d .

To underline the usefulness of this concept, let us give some examples for d . Let K be any point in R^2 . The *Moscow metric* with respect to K induces *d-straight* curves composed of pieces straight toward K or radially around K of minimal total euclidean length. Figure 40 depicts

a *d-straight* curve (dashed) between two points x and y and a Voronoi diagram (solid) for eight sites in this metric. For the *geodesic distance* among polygonal obstacles, *d-straight* curves are the minimum euclidean length connections avoiding any edge of the polygons (compare Figure 26). Also of interest are *composite metrics* where, for instance, distances are measured in the L_1 -metric in some portion of R^2 and in the L_2 - (i.e., euclidean) metric in the complement. Here, *d-straight* curves are composed of those in L_1 and L_2 such that curve length is minimized. In all three examples, the respective disks are simply connected. As a consequence, the resulting Voronoi diagrams—except for the geodesic distance function that fails to be computationally simple—can be computed in optimal $O(n \log n)$ time and $O(n)$ space by divide and conquer. Thereby, the underlying set of point sites has to be divided into subsets by curves whose intersections with any disk for d is either connected or empty. Consult Klein [1989] for further details. We pose it as an open question to find equivalent characterizations for metrics whose Voronoi diagrams are constructable by divide and conquer in optimal time.

3.3 Deformation of the Voronoi Diagram: Plane-Sweep Technique

The variety of techniques that can be used for constructing Voronoi diagrams is possibly as fascinating as the diagrams themselves. The construction of the classical planar Voronoi diagram by means of divide and conquer or via three-dimensional convex hulls are well-investigated algorithmic problems. Although the achieved complexity bounds are worst-case optimal, researchers continued considering alternative methods of construction. Aside from the incremental insertion strategy described in Sections 1.3.1 and 1.3.2, the plane-sweep technique to be discussed now stands out by its conceptual and computational simplicity. It extends nicely to various generalized types of Voronoi diagrams.

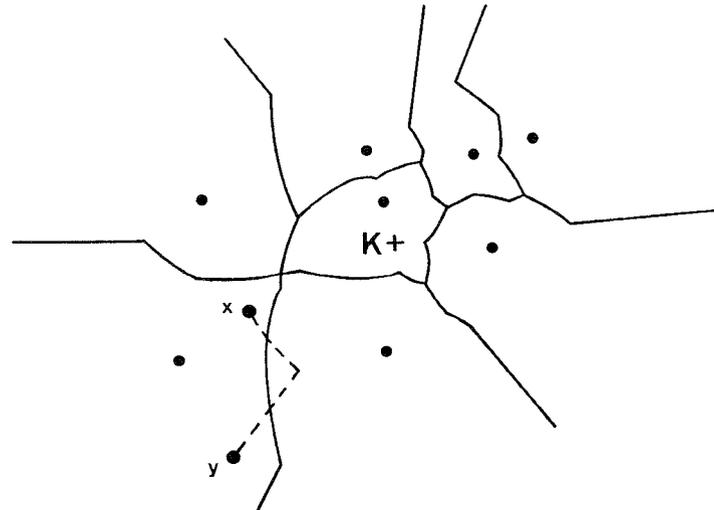


Figure 40. Voronoi diagram in the Moscow metric [Klein 1989].

3.3.1 Deformation

Let S denote a set of n point sites in R^2 and let $V(S)$ be their Voronoi diagram. As we will see, there are serious reasons for refraining from a direct construction of $V(S)$ via the plane-sweep technique. Therefore, first we introduce a continuous deformation of $V(S)$ [Fortune 1987]. Then, we describe the plane-sweep technique and its use for computing this deformation.

To explain the mechanism of deformation, the euclidean distance function with respect to the sites is interpreted in the following way. With each site $p \in S$, a cone

$\text{cone}(p)$

$$= \{(x, z) \in R^3 \mid x \in R^2, z = \delta(x, p)\}$$

is associated. $\text{Cone}(p)$ is an upwardly directed cone in R^3 with vertical axis of revolution, with apex p , and with an interior angle of $\pi/2$.¹⁴ Cones may be viewed as bivariate functions on R^2 . We define the *lower envelope* of $\{\text{cone}(p) \mid$

¹⁴ Note that the definition of $\text{cone}(p)$ agrees with that of $\text{cone}_F(p)$ used for transformable Voronoi diagrams in Section 3.1.5; F is the identity function.

$p \in S\}$ as the pointwise minimum of these functions or, equivalently, as the surface composed of that portion of each cone that lies below all other cones. From the definition of $\text{cone}(p)$ it is evident that this lower envelope projects vertically to $V(S)$ onto R^2 .

For our purposes it is preferable to project the envelope onto R^2 in a different way, namely under an angle of $\pi/4$ in positive x_2 -direction. This already gives the desired deformation $V^*(S)$ of $V(S)$. To be more precise, the deformation $*$ maps each point $x \in \text{reg}(p)$, say

$$x = \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}, \quad \text{into } x^* = \begin{pmatrix} x_1 \\ x_2 + \delta(x, p) \end{pmatrix}.$$

Let us study what happens in this process. Clearly, sites are invariant under $*$. Each separator $\text{sep}(p, q)$ is deformed into a hyperbola with bottommost point p if p is below q and bottommost point q , otherwise. (This hyperbola degenerates to a vertical half line if p and q have the same x_2 -coordinate.) Consequently, the deformed region $\text{reg}^*(p)$ of p is the intersection of hyperbolically bounded half planes of R^2 . Reference to the upper envelope model shows that $*$ preserves the topological properties of a Voronoi diagram. For instance, the interiors of the

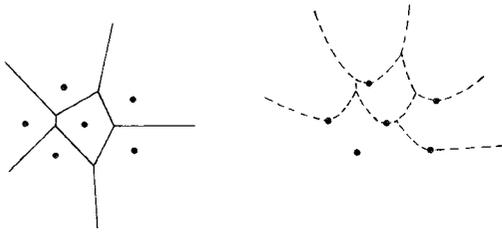


Figure 41. Deforming a Voronoi diagram [Fortune 1987].

deformed regions cover R^2 up to a set of Lebesgue measure zero. The algorithmic advantage of the deformation over the original is that the bottommost point of each region is its defining site. Exceptions are regions for the bottommost sites in S that necessarily are unbounded. Figure 41 shows the Voronoi diagram of six sites (left) and its deformation (right).

3.3.2 Plane-Sweep Technique

The properties of $V^*(S)$ are now exploited for its construction using the *plane-sweep technique*. Generally, this technique proceeds as follows. A horizontal line L is swept across the object to be constructed from below by keeping the invariant that the portion of the object below L is complete at any point in time. During the plane sweep, the cross section of L with this object has to be updated at certain critical points. We thus have to handle a one-dimensional dynamic problem instead of a two-dimensional static problem.

The applicability of the plane-sweep technique crucially depends on whether the “critical points” can be predicted. This is, for example, not the case if the Voronoi diagram of S is to be constructed in its original: A site $p \in S$ might lie above L while its region $\text{reg}(p)$ already extends to below L . And it is important to know when regions begin to intersect L in order to integrate them properly into the cross section. We do not run into such problems when constructing $V^*(S)$, however, since the bottommost point of a deformed region is just its defining site.

Initially, when L is below S , the portion of $V^*(S)$ below L contains no deformed edge. Hence the cross section is empty. As L moves upward the cross section has to be updated, either by starting a new region when L hits a site or by starting a new edge when L hits a vertex that comes from intersecting two deformed separators. The properties of $V^*(S)$ described above will ensure the correctness of this method. Efficiency is gained by organizing points of intersection of L with edges of $V^*(S)$ (the cross section) in a dictionary ordered by x_1 -coordinates and by organizing sites and already detected vertices (the critical points) in a priority queue ordered by x_2 -coordinates. There are at most $n + (2n - 4)$ critical points since $V(S)$, and thus $V^*(S)$, has at most $2n - 4$ vertices; compare the Introduction. Further, there are at most $n - 1$ points in the cross section since L cannot intersect a region of $V^*(S)$ twice. An update causes only a constant number of operations on both data structures each of which cost $O(\log n)$ time. In conclusion, $V^*(S)$ is computed in $O(n \log n)$ time and $O(n)$ space. It is clear that the original diagram $V(S)$ can be derived from its deformation in $O(n)$ time.

Fortunately, this simple construction method extends to several generalized Voronoi diagrams [Fortune 1987]. It naturally applies to the *additively weighted* type since the correspondence to lower envelopes extends provided $\text{cone}(p)$ is translated downward by the weight $w(p)$ for each site p . The intersection of $\text{cone}(p)$ with R^2 is then a circle with center p and radius $w(p)$, and indeed this type may be interpreted as the Voronoi diagram for circles under the euclidean distance function (Johnson-Mehl model, Figures 6 and 35). The time bound of $O(n \log n)$ and the space bound of $O(n)$ clearly remains unaffected.

An important type suited for a plane-sweep attack is the Voronoi diagram for noncrossing *straight-line segments* in R^2 . The distance of a point x from a segment s is measured by $\min\{\delta(x, y) \mid y \in s\}$. The region of a segment can be deformed so

as to have the lower endpoint of that segment as its bottommost point. Although details are more complicated, a reasonably simple $O(n \log n)$ time and $O(n)$ space algorithm is obtained. In particular, the *medial axis* of a simple polygon is constructable via plane-sweep: The edges of the polygon are taken as line segment sites, and the parts of the diagram outside of the polygon are ignored. Note that the separator of two segments consists of portions of straight lines and parabolas; compare Figure 25.

3.3.3 Constrained Voronoi Diagrams

A further type of Voronoi diagram, and one to which the plane-sweep technique applies particularly nicely, is the classical diagram constrained by a set of line segments [Seidel 1988]. Let S denote a set of n point sites in R^2 and let T be a set of m noncrossing line segments with their endpoints in S . Note that $m = O(n)$ since the segments form a planar graph. We view the segments in T as obstacles and define the *bounded distance* between two points $x, y \in R^2$ as

$$b(x, y) = \begin{cases} \delta(x, y), & \text{if } \overline{xy} \cap T = \emptyset, \\ \infty, & \text{otherwise.} \end{cases}$$

The *b-regions*

$$\text{reg}_b(p) = \{x \in R^2 \mid b(x, p) \leq b(x, q), q \in S\}$$

for all sites $p \in S$ define the *bounded Voronoi diagram*, $V_b(S, T)$, of S and T . *b*-regions of endpoint sites are generally nonconvex (near the corresponding obstacle), whereas *b*-regions of nonendpoint sites have to be convex. Both types of *b*-regions, and necessarily the former type, might have portions of obstacles rather than of perpendicular bisectors as edges. Clearly, $V_b(S, T)$ is a polygonal cell complex in R^2 .

The bounded Voronoi diagram is now modified to the *constrained Voronoi diagram*, $V_c(S, T)$, of S and T by modifying, for each obstacle $t \in T$, the *b*-

regions it supports. Let t support $\text{reg}_b(p_1), \dots, \text{reg}_b(p_k)$ from the left and $\text{reg}_b(q_1), \dots, \text{reg}_b(q_l)$ from the right. The former *b*-regions are extended to the left of t as if only sites p_1, \dots, p_k were present, and the latter *b*-regions are extended to the right of t as if only sites q_1, \dots, q_l were present. Note that $p_i = q_j$ has to occur twice, namely, for the endpoints r and s of t . So $\text{reg}_b(r)$ and $\text{reg}_b(s)$ are extended to both sides of t . The *c-region*, $\text{reg}_c(p)$, of a site $p \in S$ is defined as the union of $\text{reg}_b(p)$ and its extensions with respect to all obstacles. *c*-regions clearly may overlap, so they fail to define a cell complex and the graph defined by their edges is nonplanar. See Figure 42 illustrating the bounded Voronoi diagram (solid) and the constrained Voronoi diagram (solid or dashed or dotted) for 11 sites and 2 obstacles (bold).

The significance of $V_c(S, T)$ is due to its dual structure, the *constrained Delaunay triangulation* of S and T . Intuitively, this triangulation is as similar as possible to the classical Delaunay triangulation but integrates the obstacles in T , a structure with several practical applications. Formally, it consists of the obstacle segments in T and, in addition, of all edges between sites $p, q \in S$ that have $b(p, q) < \infty$ and that lie on a circle enclosing only sites $r \in S$ with at least one of $b(r, p), b(r, q) = \infty$. The interested reader may verify that two sites are connected in this triangulation if and only if their perpendicular bisector contributes an edge to the constrained Voronoi diagram. Note that the bisector of the endpoint sites of an obstacle may contribute two edges (on either side of the obstacle) rather than only one. Since S contains n sites, T contains m obstacles, and no triangulation of n points can have more than $3n - 6$ edges, we conclude that $V_c(S, T)$ realizes at most $3n + m - 6$ edges and thus has a size of $O(n)$. Figure 27 shows the constrained Delaunay triangulation that corresponds to the constrained Voronoi diagram in Figure 42.

Let us now come to the plane-sweep construction of $V_c(S, T)$. To aid the

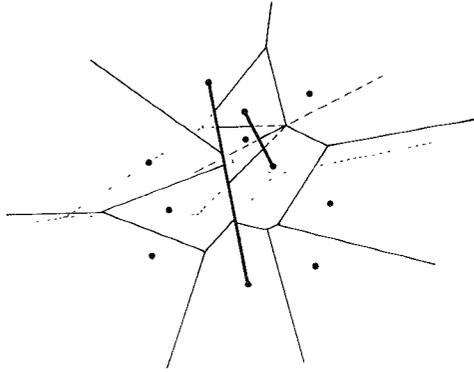


Figure 42. Bounded and constrained Voronoi diagram [Seidel 1988].

intuition, we think of $V_c(S, T)$ as being embedded into $m + 1$ parallel planes in the following way. One plane, call it H_0 , contains the bounded Voronoi diagram $V_b(S, T)$. Each of the m planes, H_t , for the obstacle $t \in T$ contains the diagram, V_t , induced by the extensions with respect to t for all b -regions supported by t . Clearly, this embedding comprises the same information as is inherent in $V_c(S, T)$. The idea now is to sweep H_0 and all H_t simultaneously by (essentially one and the same) horizontal line L in order to construct $V_b(S, T)$ and all V_t , for $t \in T$, separately. Again these $m + 1$ diagrams are not constructed directly but via their deformations $V_b^*(S, T)$ and V_t^* that come from mapping upward, within the respective plane, each point x inside an (extension of a) b -region $\text{reg}_b(p)$ by $\delta(x, p)$. Since an extended b -region is just a classical Voronoi region, its deformation has the defining site as the bottommost point (unless the site itself is bottommost for the respective plane). In analogy to the classical Voronoi diagram, regions are created as sites are hit by L , and edges are created as L hits intersections of deformed bisectors. One must, however, take care that edges are assigned correctly to their embedding planes. When a deformed edge in H_0 meets a deformed obstacle t^* , then its construction is continued within H_t and vice versa. The number of critical

points arising during the construction of $V_b^*(S, T)$ and all V_t^* is proportional to the size of $V_c(S, T)$ and thus is $O(n)$.

Using appropriate data structures supporting the $m + 1$ plane-sweeps allows us to implement the operations at each critical point in $O(\log n)$ time so an $O(n \log n)$ time and $O(n)$ space algorithm for computing $V_c(S, T)$ is obtained. In particular, the constrained Delaunay triangulation of S and T is computable within these bounds since it can be obtained in $O(n)$ time from $V_c(S, T)$ by exploiting duality.

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