Oriented Matroids Today

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Abstract

This *dynamic survey* offers an "entry point" for current research in oriented matroids. For this, it provides updates on the 1993 monograph "Oriented Matroids" by Björner, Las Vergnas, Sturmfels, White & Ziegler [73], in three parts:

1. a sketch of a few "Frontiers of Research" in oriented matroid theory,
2. an update of corrections, comments and progress as compared to [73], and
3. an extensive, complete and up-to-date bibliography of oriented matroids, comprising and extending the bibliography of [73].

1 Introduction(s).

Oriented matroids are both important and interesting objects of study in Combinatorial Geometry, and indispensable tools of increasing importance and applicability for many other parts of Mathematics. The main parts of the theory and some applications were, in 1993, compiled in the quite comprehensive monograph by Björner, Las Vergnas, Sturmfels, White & Ziegler [73]. For other (shorter) introductions and surveys, see Bachem & Kern [29], Bokowski & Sturmfels [132], Bokowski [104], Goodman & Pollack [307], Ziegler [657, Chapters 6 and 7], and, most recently, Richter-Gebert & Ziegler [517].

This *dynamic survey* provides three parts:

1. a sketch of a few "Frontiers of Research" in oriented matroid theory,
2. an update of corrections, comments and progress as compared to [73], and
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2 What is an Oriented Matroid?

Let $V = (v_1, v_2, \ldots, v_n)$ be a finite, spanning, sequence of vectors in $\mathbb{R}^r$, that is, a finite *vector configuration.* With this vector configuration, one can associate the following sets of data, each of them encoding the *combinatorial structure* of V.

- The *chirotope* of V is the map

$$\begin{array}{rcl} \chi_V : \{1,2,\ldots,n\}^r & \longrightarrow & \{+,-,0\} \\ (i_1, i_2, \ldots, i_r) & \longmapsto & \mathrm{sign}(\det(v_{i_1}, v_{i_2}, \ldots, v_{i_r})) \end{array}$$

  that records for each r-tuple of the vectors whether it forms a positively oriented basis of $\mathbb{R}^r$, a basis with negative orientation, or not a basis.
- The set of *covectors* of V is

$$\mathcal{V}^*(V) \quad := \quad \big\{\big(\mathrm{sign}(a^t v_1), \ldots, \mathrm{sign}(a^t v_n)\big) \in \{+,-,0\}^n : a \in \mathbb{R}^n\big\},$$

  that is, the set of all partitions of V (into three parts) induced by hyperplanes through the origin.
- The collection of *cocircuits* of V is the set

$$\mathcal{C}^*(V) \;:=\; \big\{\big(\mathrm{sign}(a^t v_1), \ldots, \mathrm{sign}(a^t v_n)\big) \in \{+,-,0\}^n : a \in \mathbb{R}^n \text{ is orthogonal to a hyperplane spanned by vectors in } V\big\},$$

  of all partitions by "special" hyperplanes that are spanned by vectors of the configuration V.
- The set of *vectors* of V is

$$\mathcal{V}(V) \quad := \quad \big\{\big(\mathrm{sign}(\lambda_1), \ldots, \mathrm{sign}(\lambda_n)\big) \in \{+,-,0\}^n : \lambda_1 v_1 + \ldots + \lambda_n v_n = 0 \;\text{ is a linear dependence between vectors in } V\big\}.$$

- The set of *circuits* is

$$\mathcal{C}(V) \quad := \quad \big\{\big(\mathrm{sign}(\lambda_1), \ldots, \mathrm{sign}(\lambda_n)\big) \in \{+,-,0\}^n : \lambda_1 v_1 + \ldots + \lambda_n v_n = 0 \;\text{ is a } \textit{minimal} \text{ linear dependence between vectors in } V\big\}.$$

A simple, but basic, result now states that all of these sets of data are equivalent, except for a global sign change that identifies χ with $-\chi$. Thus whenever one of the data

$$\{\chi_V, -\chi_V\}, \qquad \mathcal{V}^*(V), \qquad \mathcal{C}^*(V), \qquad \mathcal{V}(V), \qquad \text{or} \qquad \mathcal{C}(V)$$

is given, one can from this uniquely reconstruct all the others.

Furthermore, one has **axiom systems** (see [73, Chap. 3]) for *chirotopes*, *covectors*, *cocircuits*, *vectors* and *circuits* that are easily seen to be satisfied by the corresponding collections above. Thus there are combinatorial structures, called **oriented matroids**, that can equivalently be given by any of these five different sets of data, and defined/characterized in terms of any of the five corresponding axiom systems. (The proofs for the equivalences between these data sets resp. axiom systems are not simple.)

Vector configurations as discussed above give rise to oriented matroids of *rank* r on n *elements* (or: on a *ground set* of size n). Usually the ground set is identified with $E = \{1, 2, \ldots, n\}$.

Equivalent to vector configurations, one has the model of (real, linear, essential, oriented) *hyperplane arrangements*: finite collections $\mathcal{A} := (H_1, H_2, \ldots, H_n)$ of hyperplanes (linear subspaces of codimension one) in $\mathbb{R}^r$, with the extra requirement that $H_1 \cap \ldots \cap H_n = \{0\}$, and with a choice of a positive halfspace H_i^+ for each of the hyperplanes. In fact, every vector configuration gives rise to such an arrangement via $H_i^+ := \{x \in \mathbb{R}^r : v_i^t x \geq 0\}$, and from an oriented hyperplane arrangement we recover a vector configuration by taking the positive unit normals.

More specialized, one has the model of *directed graphs*: if $D = (V, A)$ is a finite directed graph (with vertex set $V = \{0, 1, 2, \ldots, r\}$ and arc set $A = \{a_1, \ldots, a_n\} \subseteq V^2$), then one has the obvious "directed circuits" in the digraph that give rise to circuits in the sense of sign vectors in $\mathcal{C}(V) \subseteq \{+, -, 0\}^n$, while directed cuts give rise to covectors, and minimal directed cuts give rise to cocircuits. Thus one obtains the oriented matroid of a digraph, which can also, equivalently, be constructed by associating with each arc (i, j) the vector $e_i - e_j \in \mathbb{R}^r$, where we take e_i to be the i-th coordinate vector in $\mathbb{R}^r$ for $i \geq 1$, and $e_0 := 0$.

Although the axiom systems of oriented matroids describe the data arising from vector configurations very well, it is not true that every oriented matroid corresponds to a real vector configuration. In other words, there are oriented matroids that are not *realizable*. This points to basic theorems and problems in Oriented Matroid Theory:

- The *Topological Representation Theorem* (see [73, Chap. 5]) shows that while real vector configurations can equivalently be represented by *oriented hyperplane arrangements*, general oriented matroids can be represented by *oriented arrangements of pseudo-hyperplanes*.
- There is no finite set of axioms that would characterize the oriented matroids that are representable by vector configurations. In fact, even for $r = 3$ there are oriented matroids on n elements that are *minimally non-realizable* for arbitrarily large n.
- The *realization problem* is a difficult algorithmic task: for a given oriented matroid, to decide whether it is realizable, and possibly find a realization. This statement is a by-product of the constructions for the Universality Theorem for oriented matroids, see below.

3 Some Frontiers of Research.

Currently there is substantial research done on a variety of aspects and questions; among them are several deep problems of oriented matroid theory that were thought to be both hard and fundamental, and are now gradually turning out to be just that.

Here I give short sketches and a few pointers to the (very recent) literature, for just a few selected topics. (By construction, the selection is very much biased. I plan to expand and update regularly. Your help and comments are essential for that.)

3.1 Realization spaces.

Mnëv's Universality Theorem of 1988 [466] states that every primary semialgebraic set defined over $\mathbb{Z}$ is "stably equivalent" to the realization space of some oriented matroid of rank 3. In other words, the semialgebraic sets of the form

$$\mathcal{R}(X) \quad := \quad \{Y \in \mathbb{R}^{3\times n} : \mathrm{sign}(\det(X_{i,j,k})) = \mathrm{sign}(\det(Y_{i,j,k})) \text{ for all } 1 \leq i < j < k \leq n\},$$

for real matrices $X \in \mathbb{R}^{3\times n}$, can be arbitrarily complicated, both in their topological and their arithmetic properties. Mnëv's even stronger Universal Partition Theorem [467] announced in 1991 says that essentially every semialgebraic family appears in the stratification given by the determinant function on the (3×3)-minors of $(3 \times n)$-matrices.

These results are fundamental and far-reaching. For example, via oriented matroid (Gale) duality they imply universality theorems for d-polytopes with $d{+}4$ vertices.

For some time, no complete proofs were available. This has only recently changed with the complete proof of the Universal Partition Theorem by Günzel [275] and by Richter-Gebert [512]. Richter-Gebert [511, Sect. 2.5] has also — finally! — provided a suitable notion of "stable equivalence" of semialgebraic sets that is *weak enough* to make the Universality Theorems true, and *strong enough* to imply both homotopy equivalence and arithmetic equivalence (i.e., it preserves the existence of K-rational points in the semialgebraic set for every subfield K of $\mathbb{R}$).

Further, surprising recent progress is now available with Richter-Gebert's [511, 516] Universality Theorem (and Universal Partition Theorem) for 4-dimensional polytopes, and related to this his Non-Steinitz theorem for 3-spheres. (See [276] for a second proof.)

Here are two major challenges that remain in this area:

- To construct and understand the smallest oriented matroids with non-trivial realization spaces. The smallest *known* examples are Suvorov's [589] oriented matroid of rank 3 on 14 points with a disconnected realization space (see also [73, p. 365]), and Richter-Gebert's [513] new example Ω_{14}^{+} with the same parameters, which additionally has rational realizations, and a non-realizable symmetry.
- To provide Universality Theorems for *simplicial* 4-dimensional polytopes (the Bokowski-Ewald-Kleinschmidt polytope [109] is still the only simplicial example known with a non-trivial realization space; see also Bokowski & Guedes de Oliveira [111]).

3.2 Extension spaces and MacPhersonians.

Quite diverse lines of thinking lead to the consideration of *spaces of oriented matroids* and their topological structures. Here the basic construction takes, for example,

- for the *MacPhersonian* $MP(n, r)$ the set of all oriented matroids of rank r on a fixed set of n elements,
- for the *extension space* $\mathcal{E}(\mathcal{M})$ the set of all non-trivial single element extensions of a fixed oriented matroid $\mathcal{M}$.

In each case one obtains a partially ordered set by consideration of rank-preserving weak maps [73, Section 7.7], and from this a topological space by taking the order complex (the simplicial complex given by the chains in the poset; see Björner [70]). Basic conjectures in the field are that

- the MacPhersonian $MP(n, r)$ should have the homotopy type, or at least the $\mathbb{Z}/2$-cohomology, of the Grassmannian $G_r(\mathbb{R}^n)$,
- the extension space $\mathcal{E}(\mathcal{M})$ should have the homotopy type of a sphere S^{r-1}, if $\mathcal{M}$ is realizable.

Note that if $\mathcal{M}$ is an oriented matroid of rank r on a set of n elements, then $\mathcal{E}(\mathcal{M})$ naturally appears as a subspace of $MP(n+1, r)$.

The first construction (and terminology) is motivated by MacPherson's [439, 282] theory of "combinatorial differential manifolds," in which oriented matroids are used as a substitute for smooth structure, and thus cohomology classes of the MacPhersonians appear as characteristic classes. Extension spaces are, for example, closely related to zonotopal tilings (via the Bohne-Dress Theorem, see below) and to oriented matroid programs; see Sturmfels & Ziegler [588].

The spaces to be considered here have a lot of interesting structure, but they are huge and hard to treat as global objects, which may account for some of the difficulty of their study. Nevertheless, there is quite some progress in recent work, in particular in the situation of low rank, by Babson [23] and Anderson [12, 13] (on MacPhersonians) and in Sturmfels & Ziegler [588] and Mnëv & Richter-Gebert [468] (on extension spaces). A brief survey is in Mnëv & Ziegler [469].

The problems arising here have close connections to a classical problem of oriented matroid theory: Las Vergnas' conjectures that every oriented matroid has at least one mutation (simplicial tope) and that the set of uniform oriented matroids of rank r on a given finite set is connected under performing mutations. In fact, if these conjectures are false, then the MacPhersonian cannot be connected! As for the Las Vergnas conjecture, Bokowski [102] and Richter-Gebert [507] have the strongest results; more work is neccessary.

Further work also remains in the understanding of weak and strong maps — currently the only comprehensive source is [73, Section 7.7]. One still has to derive structural information from the failure of Las Vergnas' strong map factorization conjecture (disproved by Richter-Gebert in [507]) and derive criteria for situations where factorization is possible.

3.3 Affine and infinite oriented matroids.

The Bohne-Dress Theorem, announced by Andreas Dress at the 1989 "Combinatorics and Geometry" Conference in Stockholm, provides a bijection between the zonotopal tilings of a fixed d-dimensional zonotope Z and the single-element liftings of the realizable oriented matroid associated with Z. This theorem turned out to be, at the same time,

- fundamental (see e. g. the connection to extension spaces of oriented matroids [588]),
- "intuitively obvious" (just draw pictures!), and
- surprisingly hard to prove; see Bohne [93] and Richter-Gebert & Ziegler [515].

This theorem leads to several new areas of study. On the one hand, the classification and enumeration of rhombic tilings of a hexagon relates to the theory of plane partitions and symmetric functions; see e.g. Elnitzky [243], Edelman & Reiner [228].

On the other hand, there is a definite need for a better understanding of zonotopal tilings of the entire plane (or of $\mathbb{R}^d$). Two different approaches have been started by Bohne [94, Kapitel 5] and by Crapo & Senechal [193], but no complete picture has emerged, yet. This is of interest, for example, in view of the mathematical problems posed by understanding quasiperiodic tilings and quasicrystals; see Senechal [548, 549].

3.4 Realization algorithms.

The realizability problem — given a "small" oriented matroid, find a realization or prove that none exists — is a key problem not only in oriented matroid theory, but also for various applications, such as the classification of "small" simplicial spheres into polytopal and non-polytopal ones (see Bokowski & Sturmfels [130, 132], Altshuler, Bokowski & Steinberg [11], Bokowski & Shemer [125]). The universality theorems mentioned above tell us that the problem is hard: in fact, in terms of Complexity Theory is just as hard as the "Existential Theory of the Reals," the problem of solving general systems of algebraic equations and inequalities over the reals. While it is not known whether the problem over $\mathbb{Q}$ is at all algorithmically solvable (see Sturmfels [579]), there are algorithms available that (at least theoretically) solve the problem over the reals. For the general problem Basu, Pollack & Roy [43] currently have the best result:

> Let $\mathcal{P} = \{P_1, \ldots, P_s\}$ be a set of polynomials in $k < s$ variables each of degree at most d and each with coefficients in a subfield $K \subseteq \mathbb{R}$.
> There is an algorithm which finds a solution in each connected component of the solution set, for each sign condition on $P_1, \ldots, P_s$, in at most $\binom{O(s)}{k} s\, d^{O(k)} = (s/k)^k s\, d^{O(k)}$ arithmetic operations in K.

However, until now this is mostly of theoretical value. What can be done for specific, explicit, small examples? Given an oriented matroid of rank 3, it seems that

- the most efficient algorithm (in practice) currently available to *find a realization* (if one exists) is the iterative "rubber band" algorithm described in Pock [491].
- the most efficient algorithm (in practice) currently available to *show that it is not realizable* (if it isn't) is the "binomial final polynomials" algorithm of Bokowski & Richter-Gebert [117] which uses solutions of an auxiliary linear program to construct final polynomials. (An explicit example of a non-realizable oriented matroid Ω_{14}^- without a final polynomial was just recently constructed by Richter-Gebert [513].)

Neither of these two parts is guaranteed to work: but still the combination of both parts was good enough for a (still unpublished) complete classification of all 312,356 (unlabeled reorientation classes of) uniform oriented matroids of rank 3 on 10 points into realizable and non-realizable ones (Bokowski, Laffaille & Richter-Gebert [115]).

A very closely related topic is that of Automatic Theorem Proving in (plane) geometry. In fact, the question of validity of a certain incidence theorem can be viewed as the realizability problem for (oriented or unoriented) matroids of the configuration. Richter-Gebert's Thesis [505] and Wu's book [637] here present two recent (distinct) views of the topic, both with many of its ramifications.

Here we are far from having reached the full scope of current possibilites. For an (impressive) demonstration I refer to the computer geometry system CINDERELLA by Crapo & Richter-Gebert [191] based on the idea of "binomial proofs" [190]. It is amazing to see how much can be achieved here by two persons in just two summers. . .

4 Some Additions and Corrections.

In this section, I collect some notes, additions, corrections and updates to the 1993 book by Björner, Las Vergnas, Sturmfels, White & Ziegler [73]. The list is far from complete (even in view of the points that I know about), and with your help I plan to expand it in the future.

Page 220, Exercise 4.28*.

Part (a) of this was already proved by Zaslavsky [639, Sect. 9]. However, part (b) remains open and should be an interesting challenge.

Page 244, Exercise 5.2(c).

Hochstättler [355] has shown that quite general arrangements of wild spheres also yield oriented matroids.

Page 270, Proposition 6.5.1.

Felsner [251] has constructed a new and especially effective encoding scheme for wiring diagrams, which implies improved upper bound for the number of wiring diagrams and hence of simple pseudoline arrangements, namely

$$\log_2 s_n \; < \; 0.6988\, n^2.$$

Page 334, Exercises 7.15(b)$^{(*)}$ and 7.17.

An example of an oriented matroid that has a simple adjoint, but not a double adjoint was constructed by Hochstättler & Kromberg [357].

Also, they observed [358] that some assertions in Exercise 7.17 are not entirely correct: Jürgen Richter-Gebert's [505, p. 117] 8-point torus is realizable over an ordered *skew field*, but not over $\mathbb{R}$. Therefore the oriented matroid given by such a skew realization has an infinite sequence of adjoints, but it is not realizable in $\mathbb{R}^4$.

Page 337, Exercises 7.44*.

No one seems to remember the example: so consider this to be an open problem. (The non-existence of such an example is also discussed, as a Conjecture of Brylawski, in McNulty [456].)

Page 405 (top).

It is not true that the sphere $\mathcal{S} = M^9_{963}$ is neighborly: the edges 13 and 24 are missing (in the labeling used in [73]). Thus Shemer's Theorem 9.4.13 cannot be applied here. A proof that the sphere admits at most one matroid polytope, `AB`(9), was given by Bokowski [97] in 1978 (see also Altshuler, Bokowski & Steinberg [11] and Antonin [16]). It is described in detail in Bokowski & Schuchert [123]. (The oriented matroid `RS`(8) discussed in [73, Sect. 1.5] arises as a contraction of the oriented matroid `AB`(9).)

Page 413, Exercise 9.12$^{(*)}$.

Bokowski & Schuchert [123] showed that the smallest example (both in terms of its rank $r = 5$ and in terms of its number of vertices $n = 9$), is given by Altshuler's sphere M^9_{963}.

5 The Bibliography.

The purpose of the following is to keep the bibliography of the book [73] up-to-date electronically. For this, the following contains *all* the references of this book (including those which are not directly concerned with oriented matroids). Into this I have inserted all the corrections, missing references, additions and updates that I am currently aware of. Any corrections, new papers concerned with oriented matroids, and other updates that you tell me about will be entered asap. I am eager to hear about your corrections, updates and comments!

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