STATISTICAL DEPTH:
GEOMETRY OF MULTIVARIATE QUANTILES

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Outline

Statistical depth

Halfspace depth

Selected properties and problems

Halfspace depth and Floating bodies

Motivation: Grünbaum's inequality

(Dupin's) floating bodies

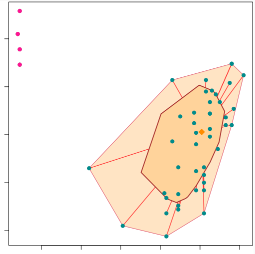
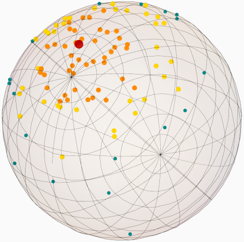
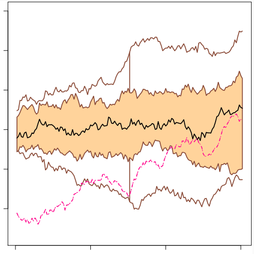
Convex floating bodies

Simplicial depth

STATISTICAL DEPTH

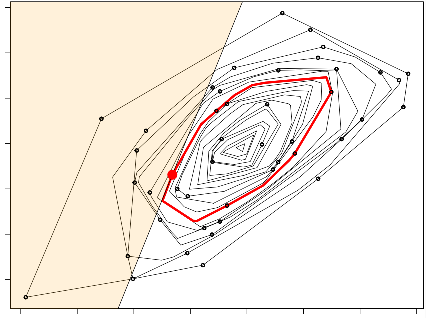
Nonparametric statistics:

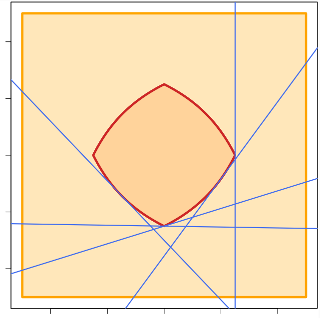
- Inference without assumptions.
- On the real line using the ordering — median, quantiles, ranks...
- What are ranks or quantiles for multivariate (non-Euclidean) data?

Statistical depth

Statistical depth function: Ordering data in multivariate spaces.



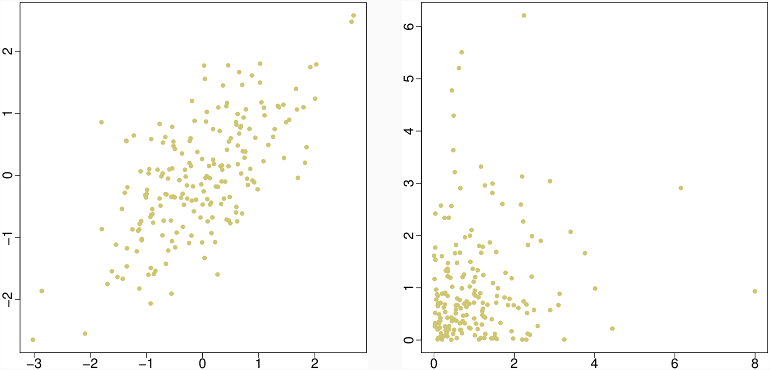


Introduced in 1975 (Tukey); studied intensively since the 1990s.

Statistical depth function

For $\mathcal{P}(\mathbb{R}^d)$ Borel probability measures on $\mathbb{R}^d$, a depth is

$$D\colon \mathbb{R}^d \times \mathcal{P}\left(\mathbb{R}^d\right) \to [0,1]\colon (x,P) \mapsto D(x,P).$$



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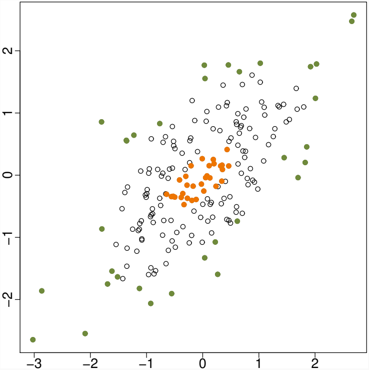
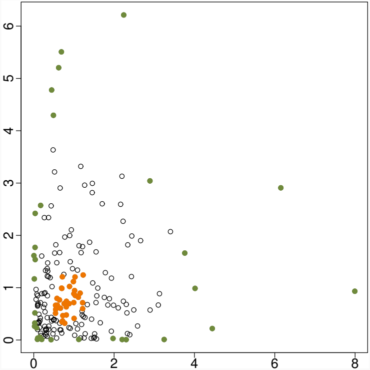
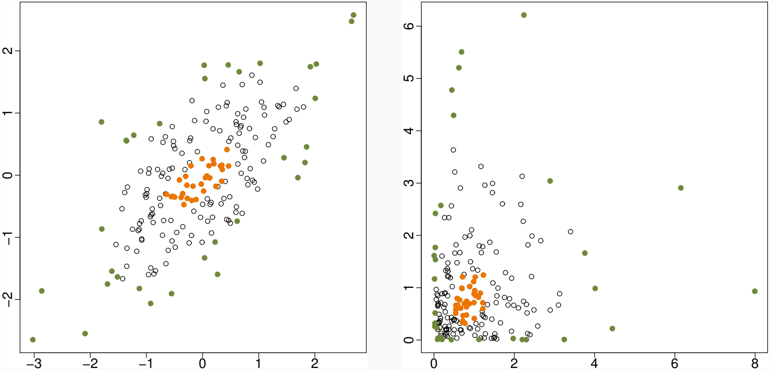




Halfspace depth

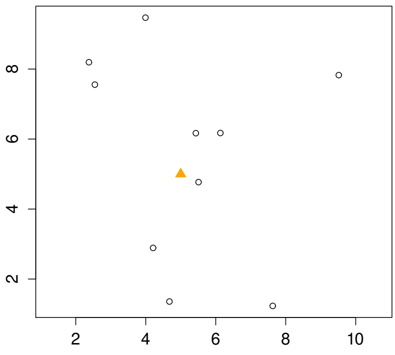
Halfspace depth (Tukey, 1975) of a point $x \in \mathbb{R}^d$ w.r.t. $P \in \mathcal{P}\left(\mathbb{R}^d\right)$

$$D(x; P) = \inf_{H \in \mathcal{H}(x)} P\left(H\right).$$



Halfspace depth

$$D\left(x; P_n\right) = \min \frac{\text{\# of observations in a halfspace that contains } x}{n}$$



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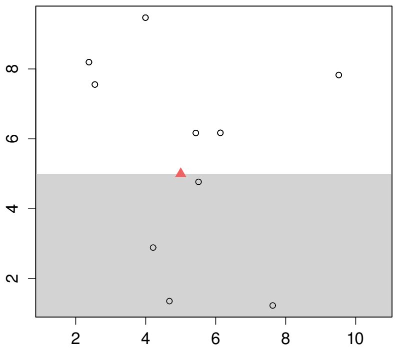

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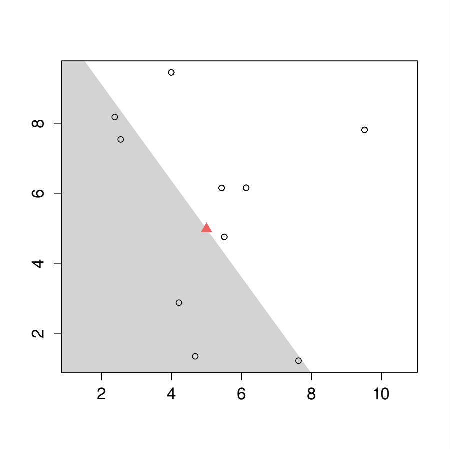

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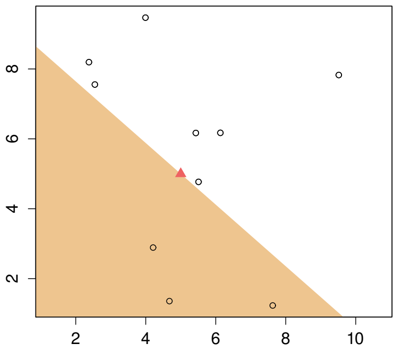
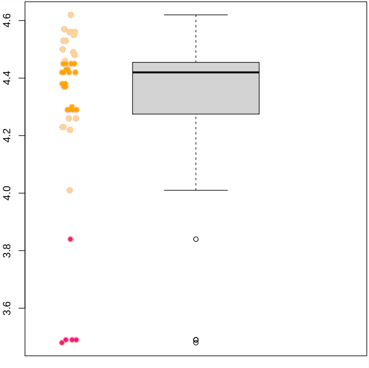
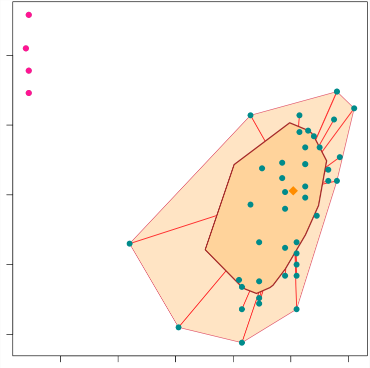


Bagplot: A multivariate boxplot (Rousseeuw et al., 1999)

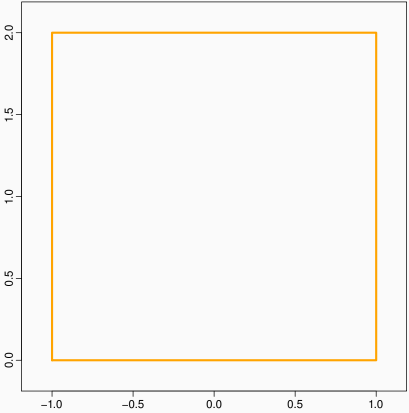




Depth: Level sets

$D(\cdot; P)$ is always quasi-concave, i.e. for each $\delta \in [0, 1]$

$$P_\delta = \left\{ x \in \mathbb{R}^d : D(x; P) \geq \delta \right\} \text{ is convex}$$



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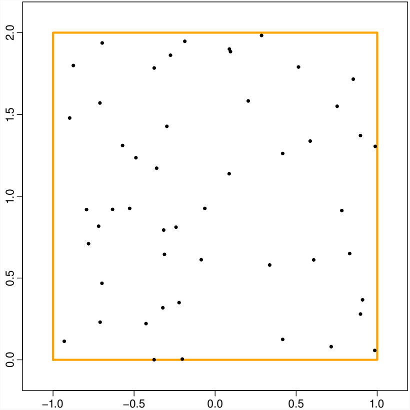

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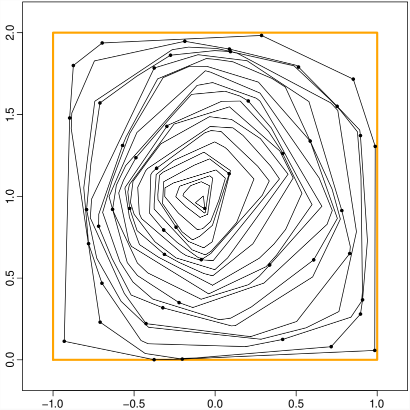

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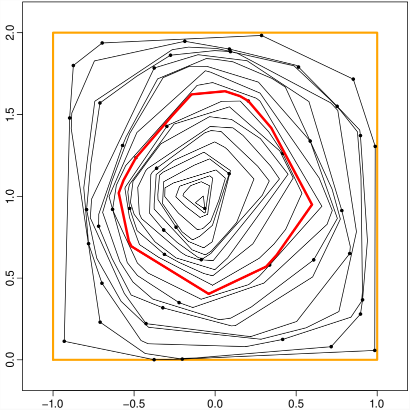

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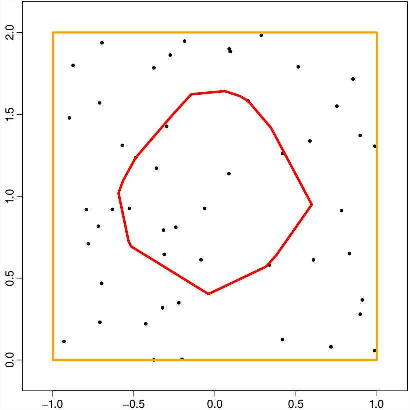

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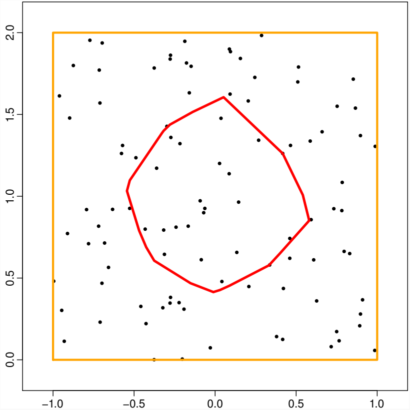

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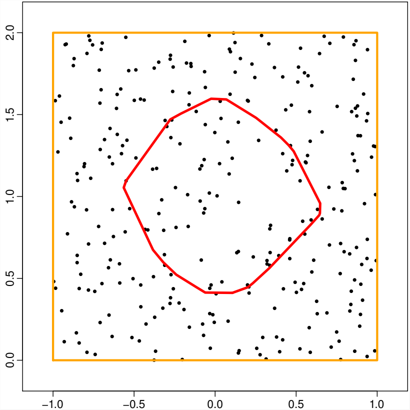

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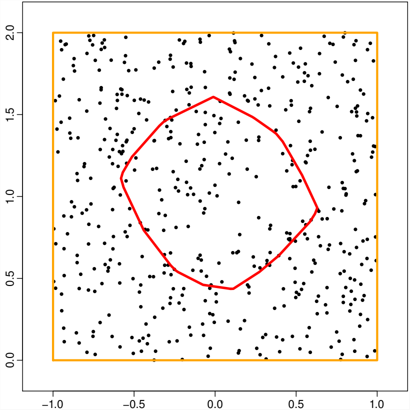

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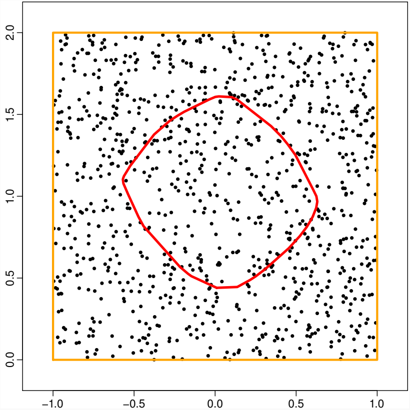
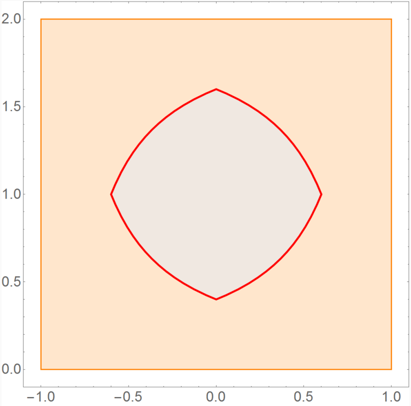


Depth: Level sets

We can write (Rousseeuw and Struyf, 1999; Zuo and Serfling, 2000)

$$P_\delta = \left\{x \in \mathbb{R}^d : D(x; P) \geq \delta\right\} = \bigcap \{H \in \mathcal{H} : P(H) > 1 - \delta\}\,.$$

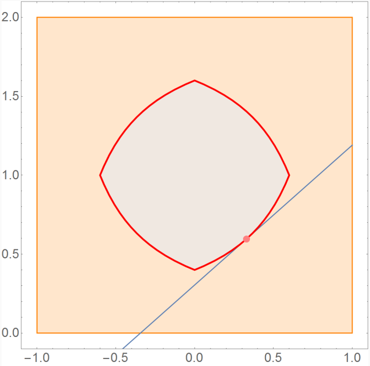


Depth: Asymptotic normality

Let $P_n \in \mathcal{P}\left(\mathbb{R}^d\right)$ be the empirical measure of n i.i.d. variables from P.

$\sqrt{n}\,(D(x;P_n) - D(x;P))$ is asymptotically normal

$\iff$ $D(x;P)$ is realised by a single halfspace $H \in \mathcal{H}(x)$ (Massé, 2004)



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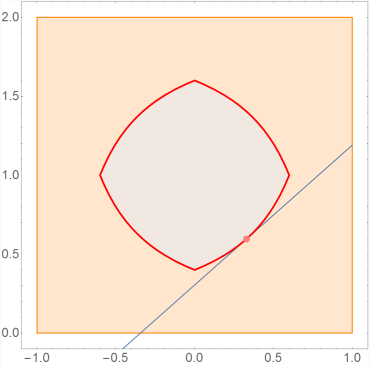
$$\iff \quad \text{the contour of } D(\cdot;P) \text{ is smooth at } x$$



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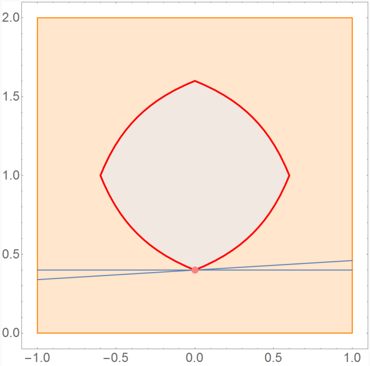
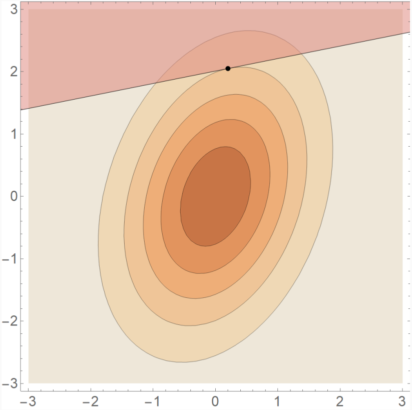


Problem: Smoothness of the depth

Elliptically symmetric distributions have smooth depth contours



Problem: Smoothness of the depth

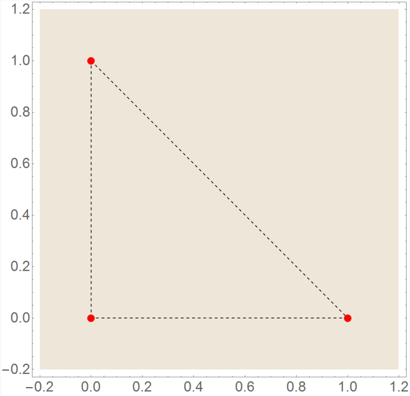
Problem (Massé and Theodorescu, 1994)

(P_1) Does there exist a non-elliptical distribution with smooth depth contours?

Problem: Depth of a median

For P uniform in the vertices of a simplex in $\mathbb{R}^d$ (Donoho and Gasko, 1992)

$$\sup_{x \in \mathbb{R}^d} D(x; P) = (d+1)^{-1} \xrightarrow[d \to \infty]{} 0$$



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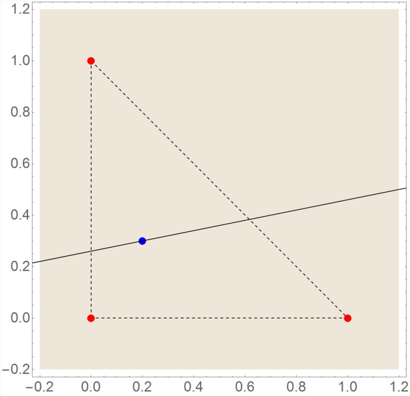


Problem: Depth of a median

Problem (Donoho and Gasko, 1992)

(P_2) The maximum depth in $\mathbb{R}^d$ is at least $1/(d+1)$. Can we say more?

Problem: Characterization conjecture

Problem (Struyf and Rousseeuw, 1999)

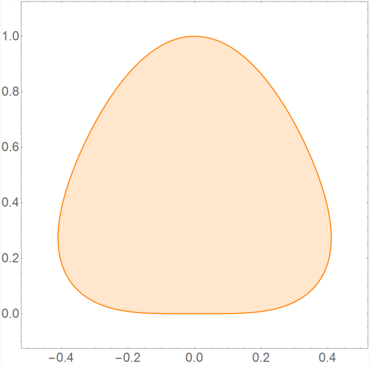
(P_3) Does for any $P \neq Q$ in $\mathcal{P}\left(\mathbb{R}^d\right)$ exist $x \in \mathbb{R}^d$ such that $D(x; P) \neq D(x; Q)$?

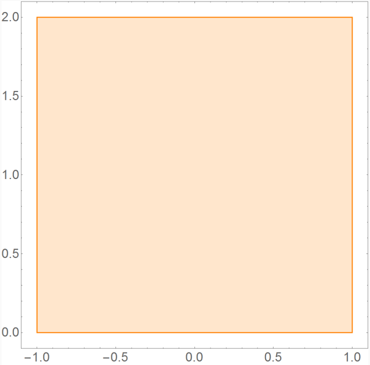
Partial answers:

- Certainly yes for $d = 1$ (there depth $\sim$ distribution function).
- Yes if P is atomic (Struyf and Rousseeuw, 1999; Koshevoy, 2002; Hassairi and Regaieg, 2007; Laketa and Nagy, 2021).
- Yes if the contours of $D(\cdot; P)$ are smooth (Kong and Zuo, 2010).
- Long conjectured general positive answer (Koshevoy, 2003; Hassairi and Regaieg, 2008; Cuesta-Albertos and Nieto-Reyes, 2008).

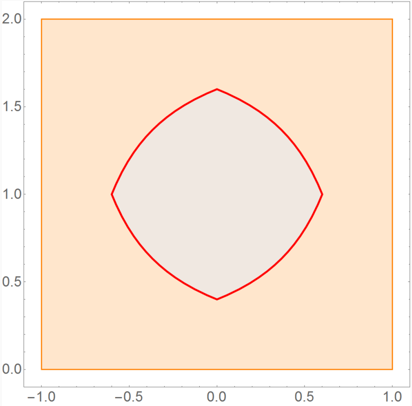
HALFSPACE DEPTH AND FLOATING BODIES

Convex body is a non-empty, compact and convex set $K \subset \mathbb{R}^d$ (Webster, 1994; Schneider, 2014).





Depth of a convex body K



Motivation: Grünbaum's inequality

Proposition (Grünbaum, 1960)

Let $K \subset \mathbb{R}^d$ be a convex body, $\operatorname{vol}(K) = 1$*, and X uniform on K. Then*

$$D(\mathrm{E}\,X; K) \geq \left(\frac{d}{d+1}\right)^d.$$

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- $\lim_{d \to \infty} \left(\frac{d}{d+1}\right)^d = \exp(-1) \approx 0.37.$

APPLICATIONS

DE GÉOMÉTRIE

ET

DE MÉCHANIQUE;

A LA MARINE, AUX PONTS ET CHAUSSÉES, ETC.,

POUR FAIRE SUITE

AUX DÉVELOPPEMENTS DE GÉOMÉTRIE,

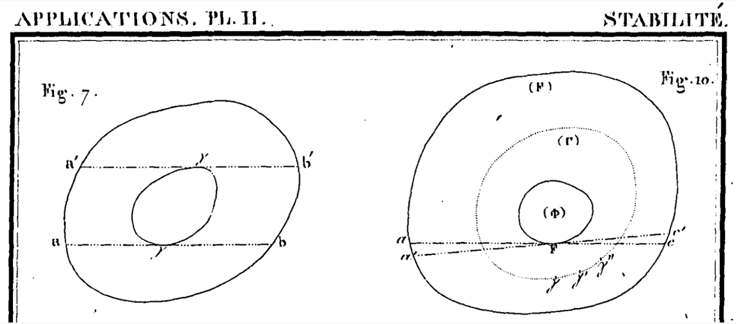
PAR CHARLES DUPIN,

Membre de l'Institut de France, Académie des Sciences; ancien Secrétaire de l'Académie Ionnienne, Associé étranger de l'Institut de Naples, Associé honoraire de l'Académie royale d'Irlande, et de la Société des Ingénieurs civils de la Grande-Bretagne, Membre des Académies royales des Sciences de Stockholm, de Turin, de Montpellier, etc., de la Société des Arts de Genève, de la Société d'Encouragement pour l'industrie française, Membre du Comité consultatif des Arts et Manufactures de France, Professeur de Méchanique au Conservatoire, Officier supérieur au corps du Génie Maritime, et Membre de la Légion-d'Honneur.

PARIS,

BACHELIER, SUCCESSEUR DE Mme. Ve. COURCIER, LIBRAIRE,
QUAI DES AUGUSTINS.

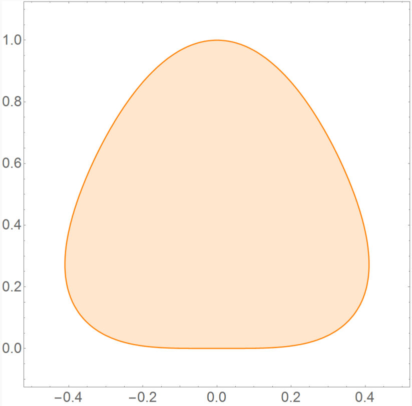
1822.



Definition (Dupin, 1822)

A convex body $K_{[\delta]}$ is the Dupin floating body of a convex body $K \subset \mathbb{R}^d$ for $\delta \in [0, \text{vol}(K)/2]$ if each supporting hyperplane of $K_{[\delta]}$ cuts off a set of volume δ from K.

Dupin's floating body of $K \subset \mathbb{R}^2$ for $\delta = 0.3$



Floating body

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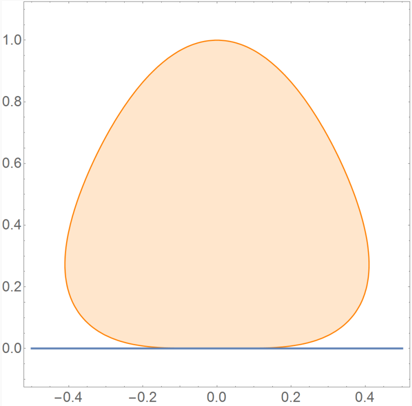

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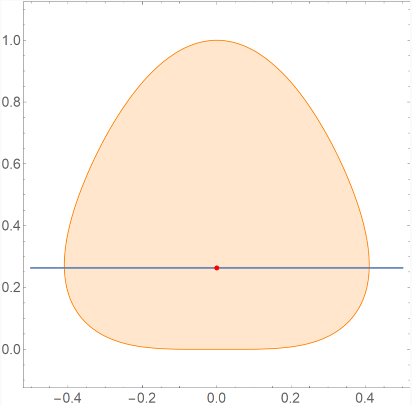

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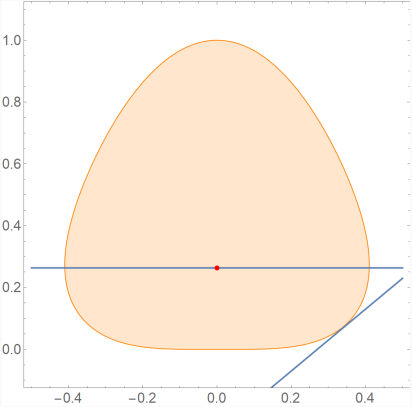

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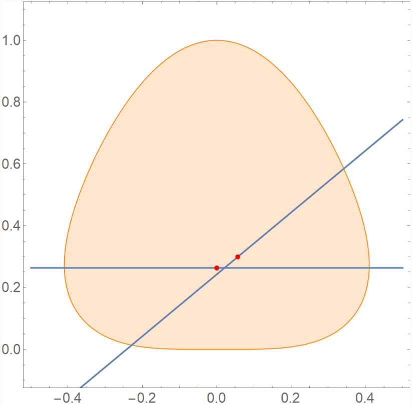

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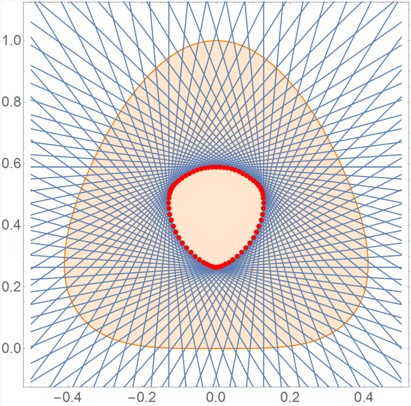

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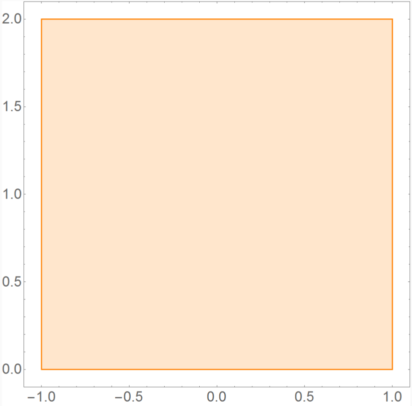

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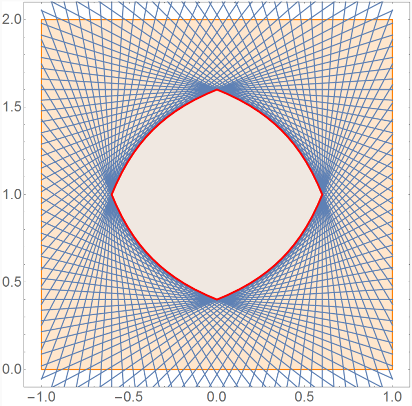


Problem: Dupin's floating body does not have to exist.

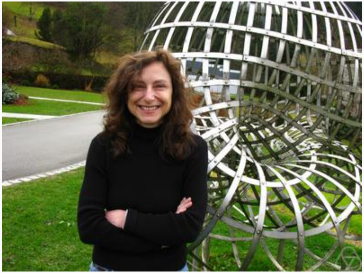
Definition (Schütt and Werner, 1990)
Let $K \subset \mathbb{R}^d$ be a convex body with $\mathrm{vol}(K) = 1$ and $\delta \in (0, 1/2)$.
The **convex floating body** of K associated with δ is given by

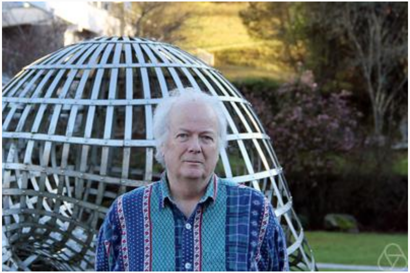
$$K_\delta = \bigcap \{H \in \mathcal{H} \colon \mathrm{vol}(K \cap H) \geq 1 - \delta\}.$$

Proposition (Schütt and Werner, 1990)

- *K_δ always exists.*
- *If $K_{[\delta]}$ exists, then $K_{[\delta]} = K_\delta$.*
- *Just as $K_{[\delta]}$, also K_δ has "nice" properties.*

Elisabeth Werner and Carsten Schütt





[1] Stanislav Nagy, Carsten Schütt, and Elisabeth M. Werner. Halfspace depth and floating body. *Statistics Surveys*, 13:52–118, 2019.

Grünbaum's inequality

- If K is a convex body, $D(\mathrm{E}\,X; K) \geq \exp(-1)$ (Grünbaum, 1960);
- Extensions to log-concave, κ-concave and quasi-concave measures and densities (Ball, 1986, 1988; Caplin and Nalebuff, 1991; Bobkov 2003, 2010);

$\Longrightarrow$ **(P$_2$)** The more concave density, the higher maximum depth.

Smoothness of floating bodies

Problem (Massé and Theodorescu, 1994)

(P_1) Does there exist a non-elliptical distribution with smooth depth contours?

Proposition (Meyer and Reisner, 1991)

Uniform distributions on smooth, symmetric, strictly convex bodies have smooth depth.

Depth characterization conjecture

Question: (Struyf and Rousseeuw, 1999)
Does for any $P \neq Q$ in $\mathcal{P}\left(\mathbb{R}^d\right)$ exist $x \in \mathbb{R}^d$ such that $D(x; P) \neq D(x; Q)$?

Positive answers for $P \in \mathcal{P}\left(\mathbb{R}^d\right)$ such that:

- $d = 1$ (there depth $\sim$ distribution function).
- P is purely atomic, with finitely many atoms.
  (Struyf and Rousseeuw, 1999; Koshevoy, 2002; Laketa and Nagy, 2021)
- P is atomic. (Cuesta-Albertos and Nieto-Reyes, 2008)
- P is properly integrable. (Koshevoy, 2003)
- P has a smooth density. (Hassairi and Regaieg, 2008)
- all Dupin's floating bodies of P exist.
  (Kong and Zuo, 2010; Nagy, Schütt, Werner, 2019)

Conjectured positive answer.

(Cuesta-Albertos and Nieto-Reyes, 2008; Kong and Mizera, 2012)

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(Cuesta-Albertos and Nieto-Reyes, 2008; Kong and Mizera, 2012)

Characterization conjecture

Question: (Struyf and Rousseeuw, 1999)

Does for any $P \neq Q$ in $\mathcal{P}\left(\mathbb{R}^d\right)$ exist $x \in \mathbb{R}^d$ such that $D(x; P) \neq D(x; Q)$?

Not for $d > 1$.

[1] Stanislav Nagy. Halfspace depth does not characterize probability distributions. *Statistical Papers*, 62:1135–1139, 2021.

[2] Stanislav Nagy. The halfspace depth characterization problem. *Nonparametric Statistics*, 379–389. Springer International Publishing. 2020.

Depth characterization: Proof I

A measure $P \in \mathcal{P}(\mathbb{R}^d)$ is called α-symmetric (Eaton, 1981) if

$$\psi(t) = \int_{\mathbb{R}^d} \exp\left(\mathrm{i}\langle t, x\rangle\right) \mathrm{d}P(x) = \xi\left(\|t\|_\alpha\right) \qquad \text{for all } t \in \mathbb{R}^d$$

for some $\xi \colon \mathbb{R} \to \mathbb{R}$. For $X = (X_1, \dots, X_d) \sim P$, these measures satisfy

$$\langle X, u\rangle \overset{d}{=} \|u\|_\alpha X_1 \qquad \text{for all } u \in \mathbb{S}^{d-1}.$$

For the depth of α-symmetric P

$$\begin{aligned} D(x; P) &= \inf_{u \in \mathbb{S}^{d-1}} \mathrm{P}\left(\langle X, u\rangle \leq \langle x, u\rangle\right) = \inf_{u \in \mathbb{S}^{d-1}} \mathrm{P}\left(\|u\|_\alpha X_1 \leq \langle x, u\rangle\right) \\ &= \mathrm{P}\left(X_1 \leq \inf_{u \in \mathbb{S}^{d-1}} \langle x, u\rangle / \|u\|_\alpha\right) = F_1\left(-\|x\|_\beta\right) \end{aligned}$$

for β the conjugate index to α, and F_1 the c.d.f. of X_1.

Depth characterization: Proof II

Fix $\gamma \in (0, 1)$ and take $\psi_\alpha(t) = \exp\left(- \|t\|_\alpha^\gamma\right)$ for $\gamma \leq \alpha \leq 1$. Then

- Measure P_α with characteristic function ψ_α exists (Lévy, 1937);
- The conjugate index to $\alpha \leq 1$ is $\beta = \infty$; and
- For the characteristic function of X_1 with $X \sim P_\alpha$ we have

$$\mathsf{E} \exp\left(\mathrm{i}\, t X_1\right) = \exp\left(- |t|^\gamma\right) \quad \text{for all } t \in \mathbb{R},$$

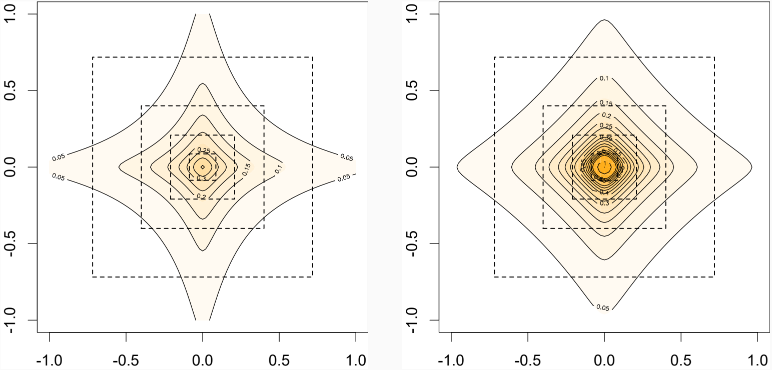
  i.e. F_1 does not depend on α.

All $P_\alpha \in \mathcal{P}\left(\mathbb{R}^d\right)$ have the same depth

$$D\left(x; P_\alpha\right) = F_1\left(- \|x\|_\infty\right) \quad \text{for all } x \in \mathbb{R}^d.$$

Depth characterization: Proof III

For $\gamma = 1/2$, the density of P_α with $\alpha = 1$ (left) and $\alpha = 1/2$ (right).

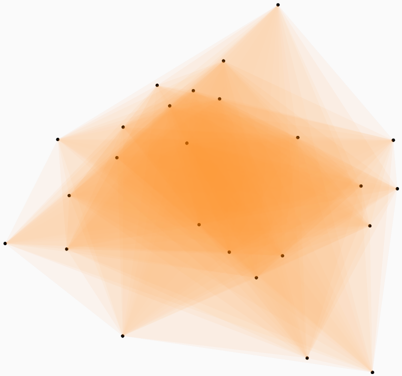


SIMPLICIAL DEPTH

Simplicial depth

Simplicial depth (Liu, 1988) of $x \in \mathbb{R}^d$ w.r.t. $P \in \mathcal{P}\left(\mathbb{R}^d\right)$ is

$$SD(x; P) = \mathrm{P}\left(x \in \triangle(X_1, \ldots, X_{d+1})\right).$$



How to compute simplicial depth?

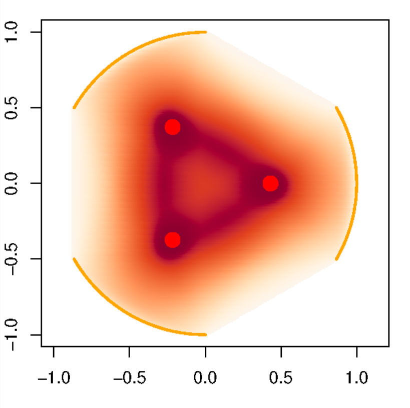
Simplicial depth (Liu, 1988) of $x = \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \in \mathbb{R}^2$ w.r.t. $P \in \mathcal{P}\left(\mathbb{R}^2\right)$ is

$$SD(x;P) = \mathrm{P}\left(\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \in \triangle\left(\begin{pmatrix} X_{1,1} \\ X_{1,2} \end{pmatrix}, \begin{pmatrix} X_{2,1} \\ X_{2,2} \end{pmatrix}, \begin{pmatrix} X_{3,1} \\ X_{3,2} \end{pmatrix}\right)\right)$$
$$= \iint \iint \iint \mathbb{I}\left[x \in \triangle\right] \,\mathrm{d}\, P(x_{1,1}, x_{1,2})\,\mathrm{d}\, P(x_{2,1}, x_{2,2})\,\mathrm{d}\, P(x_{3,1}, x_{3,2}).$$

- $d \times (d+1)$ integrals in $\mathbb{R}^d$.
- Impossible to calculate already for Gaussian distributions in $\mathbb{R}^2$.
- How does the population $SD(\cdot;P)$ even look like?

Population simplicial depth

The integrals are simpler if $P \in \mathcal{P}\left(\mathbb{R}^2\right)$ lives on a curve.

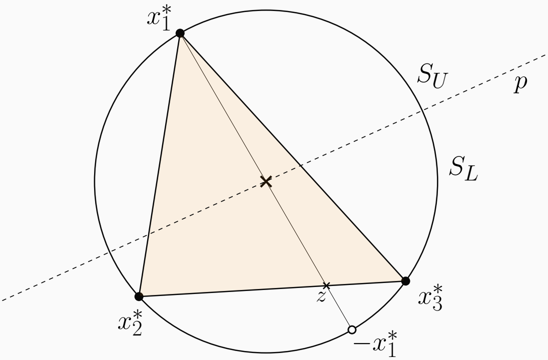


Three medians?

Computing simplicial depth exactly

We want to compute the simplicial depth in $\mathbb{R}^2$ exactly:

$$SD(x; P) = \mathrm{P}\left(x \in \triangle(X_1, X_2, X_3)\right).$$



Proposition (Mendroš and Nagy, 2024)

Let $a \in \mathbb{R}^2$ be any non-zero vector, $X \sim P \in \mathcal{P}\left(\mathbb{R}^2\right)$ be absolutely continuous and let $q = P(a^\top X > 0)$. Then

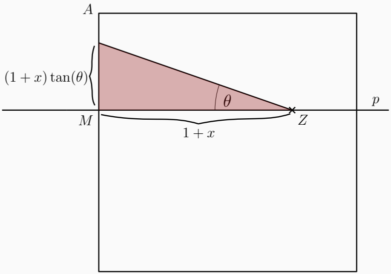
$$SD(0; P) = 6\, q \cdot (1-q)^2 \int_0^\pi G_a(\theta) \cdot (1 - G_a(\theta))\, dF_a(\theta) + 6\, q^2 \cdot (1-q) \int_0^\pi F_a(\theta) \cdot (1 - F_a(\theta))\, dG_a(\theta),$$

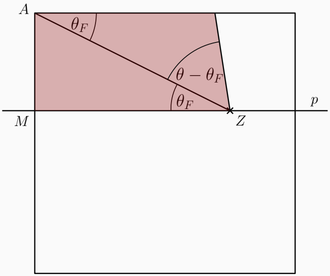
where F_a (G_a) is the upper (lower) circular distribution function of P.

[1] Erik Mendroš and Stanislav Nagy. Explicit bivariate simplicial depth. *Journal of Multivariate Analysis*, to appear, 2024.

Simplicial depth of a square

$P = \mathrm{Unif}([-1,1]^2)$: Finding the circular distribution function $F_a(\theta)$.





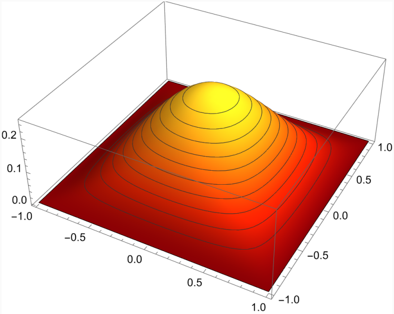
Simplicial depth of a square

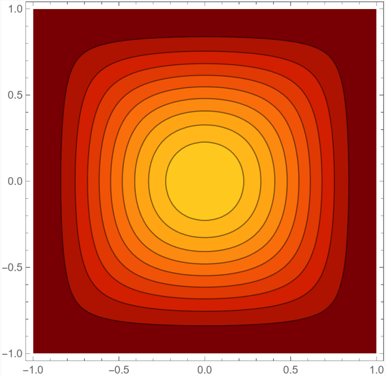
For $0 \leq x \leq 1$ and $0 \leq y \leq x$ we have

$$SD((x,y);P) =$$
$$\frac{(x-1)^2}{32}\Bigg[-\frac{2\left(3y^4(-x^2+3x+3)-y^2(7x^2+18x+9)+6x^2+9x+4\right)}{(x+1)(y^2-1)}$$
$$+3(y^2(3x-1)+x+1)\log\left(\frac{1+x}{1-x}\right)+3y(y^2(x-1)+3x+1)\log\left(\frac{1-y}{1+y}\right)\Bigg].$$

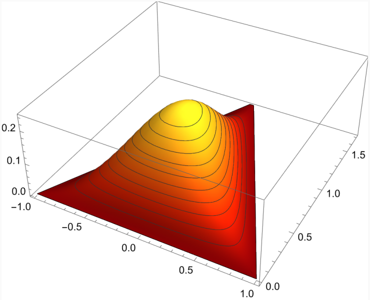
In other parts of $[-1,1]^2$ symmetrically.

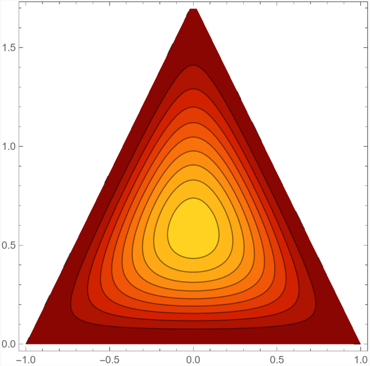
Simplicial depth of a square



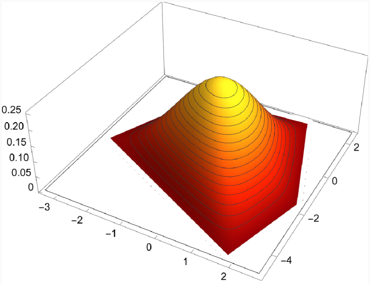


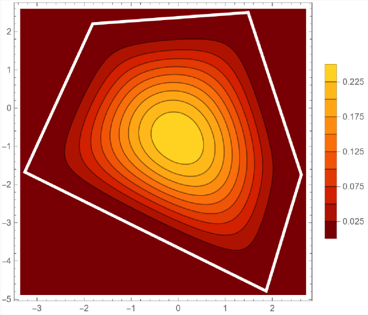
Simplicial depth of a triangle





Simplicial depth of polygons





Simplicial depth in mathematics

Simplicial depth (Liu, 1988) of $x \in \mathbb{R}^d$ w.r.t. $P \in \mathcal{P}\left(\mathbb{R}^d\right)$ is

$$SD(x; P) = \mathrm{P}\left(x \in \triangle(X_1, \dots, X_{d+1})\right).$$

- Studied since the 1950s in geometry (*stabbings*) and graph theory (*tournaments*).
- First selection lemma: $\max_{x \in \mathbb{R}^d} SD(x; P) \geq c_d > 0$,
  with $c_1 = 1/2$, $c_2 = 2/9$, $c_d = (d!)(d+1)^{-d}$ (conjectured).
- Applications to breakdown point (BP) of the simplicial median: The simplicial median is robust, but its BP decreases fast with d.

[1] Stanislav Nagy. Simplicial depth and its median: Selected properties and limitations. *Statistical Analysis and Data Mining* 16(4), 374–390, 2023.

Conclusion

Quantiles and multivariate data:

- Many different approaches; inherently geometric.
- Halfspace depth and the floating body are the same concept.
- Halfspace depth does not characterize distributions.
- Simplicial depth in $\mathbb{R}^2$ can be evaluated (sometimes).

What we do not know:

- When are floating bodies smooth?
- When does halfspace depth characterize distributions?
- Is the triangle characterized by its halfspace depth?
- How to evaluate simplicial depth in $\mathbb{R}^d$, $d > 2$?

Selected literature

[1] David L. Donoho and Miriam Gasko. Breakdown properties of location estimates based on halfspace depth and projected outlyingness. *Ann. Statist.*, 20(4):1803–1827, 1992.

[2] Branko Grünbaum. Partitions of mass-distributions and of convex bodies by hyperplanes. *Pacific J. Math.*, 10:1257–1261, 1960.

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[5] Carsten Schütt and Elisabeth M. Werner. The convex floating body. *Math. Scand.*, 66(2):275–290, 1990.

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[7] John W. Tukey. Mathematics and the picturing of data. In *Proceedings of the International Congress of Mathematicians (Vancouver, B. C., 1974), Vol. 2*, pages 523–531. Canad. Math. Congress, Montreal, Que., 1975.

More at

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and in

[1] Stanislav Nagy, Carsten Schütt, and Elisabeth M. Werner. Halfspace depth and floating body. *Statistics Surveys*, 13:52–118, 2019.

[2] Stanislav Nagy. Halfspace depth does not characterize probability distributions. *Statistical Papers*, 62:1135–1139, 2021.

[3] Stanislav Nagy. The halfspace depth characterization problem. *Nonparametric Statistics*, 379–389. Springer International Publishing. 2020.

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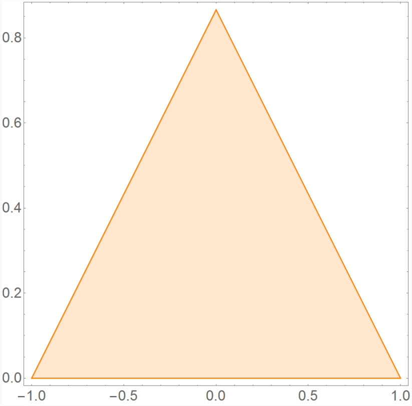
Floating body

Dupin's floating body of K does not have to exist



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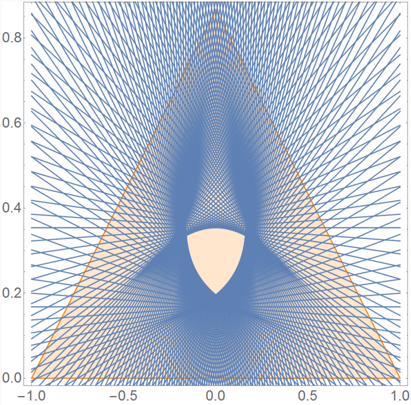

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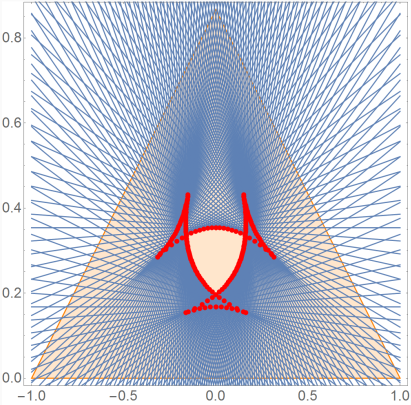

Simplicial depth of polygons