A CAROUSEL PROPERTY FOR COMPACT CONVEX SETS

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Carleton University
Algorithms Seminar

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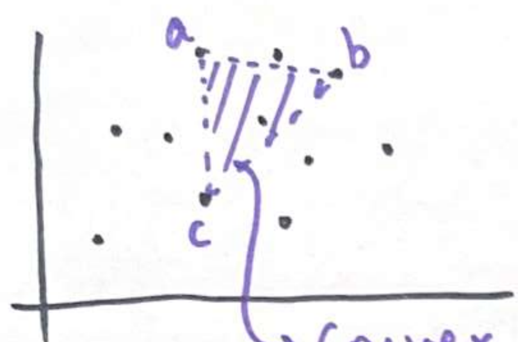
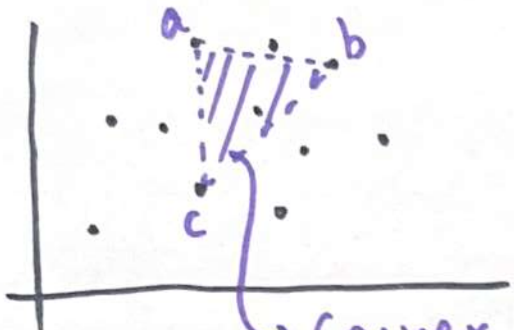
1 CONVEXITY :



Convex hull of $\{a, b, c\}$

(points in $\mathbb{R}^2$, convex hull)

① CONVEXITY :



Convex hull of $\{a, b, c\}$

$\left(\text{points in } \mathbb{R}^2 \;,\; \text{convex hull} \right)$

More generally, a <u>CONVEX</u> <u>GEOMETRY</u> is a set X and a closure operator $\phi : 2^X \to 2^X$ satisfying:

CLOSURE PROPERTIES:

$$A \subset \phi(A)$$
$$A \subset B \Rightarrow \phi(A) \subset \phi(B)$$
$$\phi(A) = \phi(\phi(A))$$

ANTI-EXCHANGE RULE: For convex A, $x, y \notin A$, $x \in \phi(A \cup \{y\})$ $\Rightarrow y \notin \phi(A \cup \{x\})$

Q. Does every convex geometry look like

$$\left\{ \begin{matrix}\text{points in}\\ \mathbb{R}^n\end{matrix} \;,\; \text{convex hull} \right\} \;?$$

$$\Big\updownarrow \cong \;?$$

$$\left\{ \begin{matrix}\text{a set}\\ X\end{matrix} \;,\; \begin{matrix}\text{closure operator}\\ \phi : 2^X \longrightarrow 2^X\end{matrix} \right\}$$

Q. Does every convex geometry look like

$$\left\{ \begin{array}{c} \text{points in} \\ \mathbb{R}^n \end{array} , \begin{array}{c} \text{convex hull} \end{array} \right\} \quad ?$$

$$\Big\updownarrow \cong \, ?$$

$$\left(\begin{array}{c} \text{a set} \\ X \end{array} , \begin{array}{c} \text{closure operator} \\ \phi : 2^X \longrightarrow 2^X \end{array} \right\}$$

A. NO.

$$\left(\{a, b\}, \phi \right) \xrightarrow{\not\cong} \left(\begin{array}{c} \text{two points} \\ \text{in } \mathbb{R}^n \end{array} , \begin{array}{c} \text{convex} \\ \text{hull} \end{array} \right)$$

$$\boxed{\phi(\{a\}) = \{a, b\}}$$

$$\phi(\{b\}) = \{b\}$$

$$\phi(\{a, b\}) = \{a, b\}$$

$$\phi(\{\}) = \{\}$$

No <u>representation</u> with points in $\mathbb{R}^n$ exists.

A. NO… but possible with CIRCLES

$$\left(\{a, b\}, \phi\right) \longrightarrow \left(\text{circles in } \mathbb{R}^2, \text{ convex hull}\right)$$

$$\phi(\{a\}) = \{a, b\}$$
$$\phi(\{b\}) = \{b\}$$
$$\phi(\{a,b\}) = \{a, b\}$$
$$\phi(\{\}) = \{\}$$

$a \longmapsto$

$b \longmapsto$

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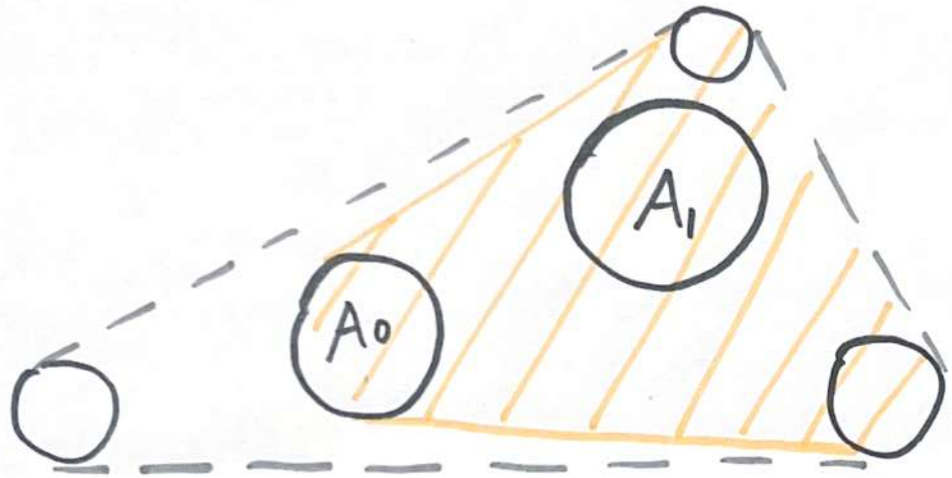
More geometry $\Longrightarrow$ More representations

Restricting to $\mathbb{R}^2$, are circles enough?

No. (ADARICHEVA-BOLAT, 2019)

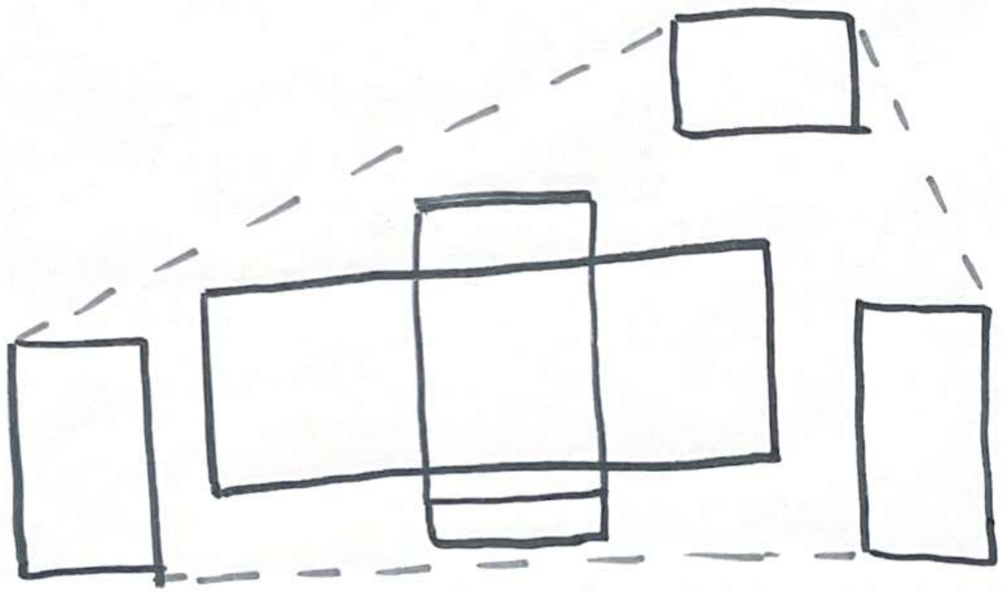


Thm. If A_0, A_1 are disks in $\mathbb{R}^2$ and G is the convex hull of three disks g_1, g_2, g_3, where $A_0, A_1 \subset \operatorname{Conv}(g_1, g_2, g_3)$, then there exist $i \in \{0,1\}$, $j \in \{1,2,3\}$ such that

$$A_i \subset \operatorname{Conv}(A_{1-i}, \{g_1, g_2, g_3\} \setminus \{g_j\})$$

More complex polygons don't have this issue.

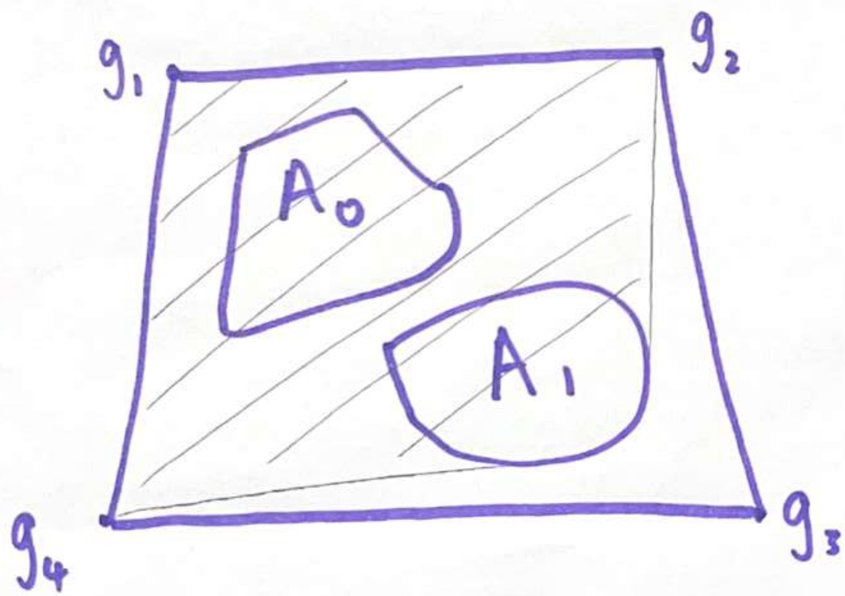
<u>Thm</u> (Richter-Rogers, 2017). Any convex geometry can be represented by n-gons in $\mathbb{R}^2$ for sufficiently large n.



The WEAK CAROUSEL RULE : Given $\mathcal{A} = \{A_0, A_1\}$ convex compact subsets of the plane, and $G = \operatorname{conv}(g_1, \dots, g_n)$ a convex n-gon containing $\mathcal{A}$, we say $(\mathcal{A}, G)$ satisfy the WCR if:

$$\exists\, i \in \{0,1\},\ j \in \{1, \dots, n\} \text{ such that}$$

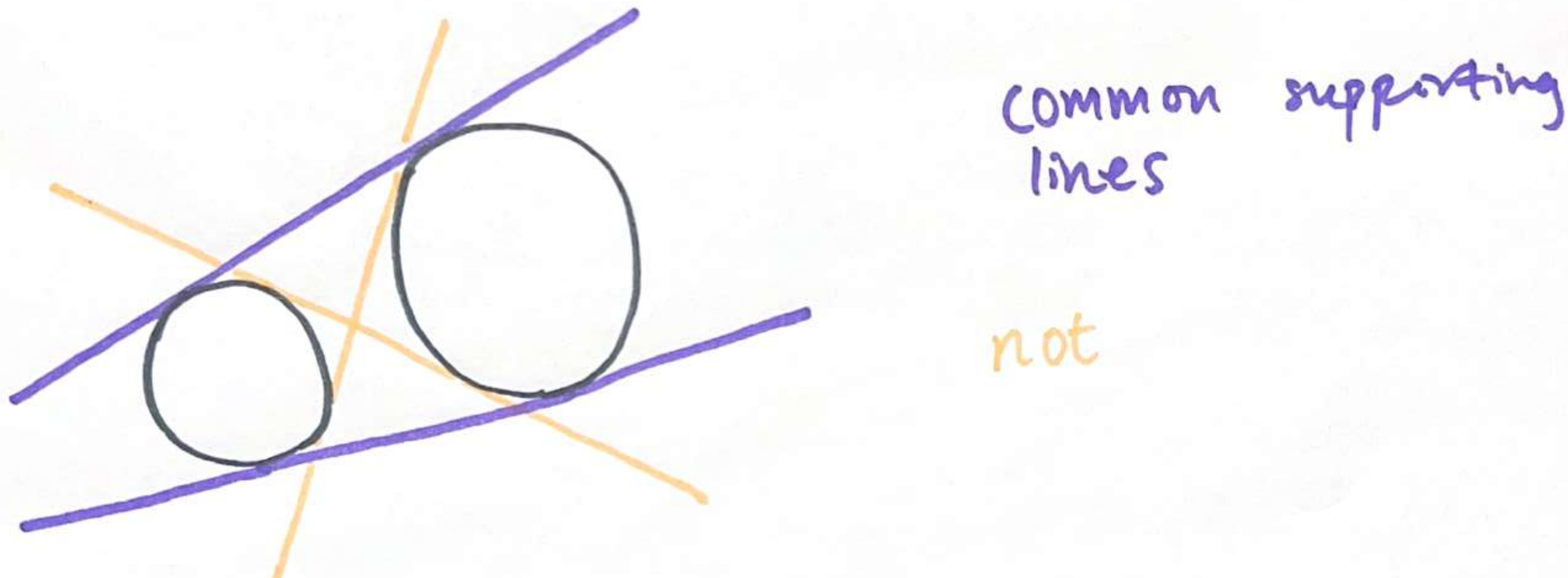
$$A_i \subset \operatorname{conv}\left(A_{1-i}, \{g_1, \dots, g_n\} \setminus \{g_j\}\right).$$



Thm. (S., 2025). Suppose

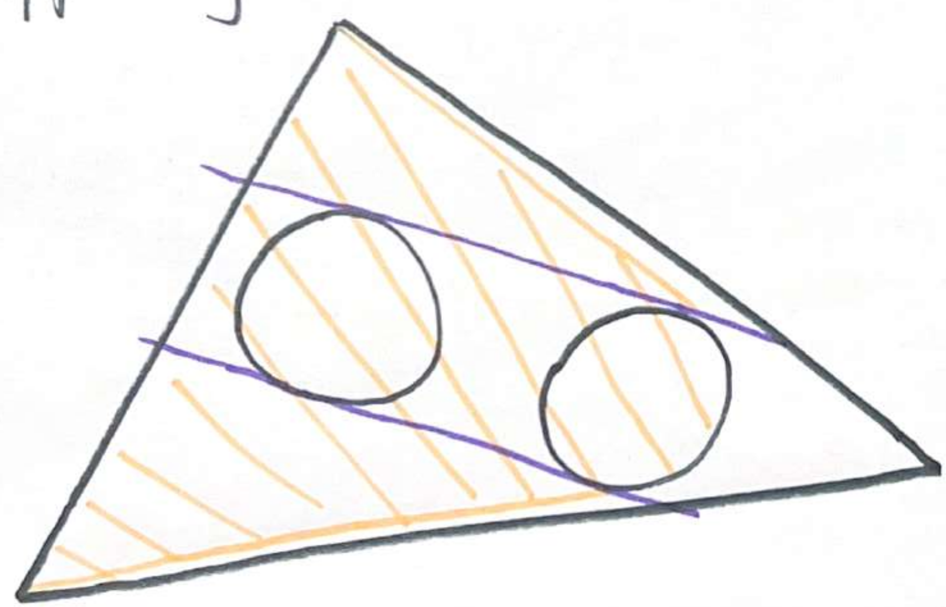
$$\#\left\{\begin{matrix}\text{common supporting}\\ \text{lines of } A_0, A_1\end{matrix}\right\} < n.$$ Then

the weak carousel rule holds.



<u>Cor.</u> (Adaricheva – Bolat, 2019). Two disks in a triangle satisfy the weak carousel rule.

Pf. Two Disks have at most two common supporting lines.



Thm (S., 2025) Let $A_0, A_1 \subset \mathbb{R}^2$ be convex and compact. Let $G = \mathrm{conv}(g_1, \dots, g_n)$ be an n-gon containing A_0, A_1. If

$$\# \left\{ \begin{array}{c} \text{common supporting} \\ \text{lines of } A_0, A_1 \end{array} \right\} < n,$$

then $\exists\, i \in \{0,1\},\ j \in \{1, \dots, n\}$ such that

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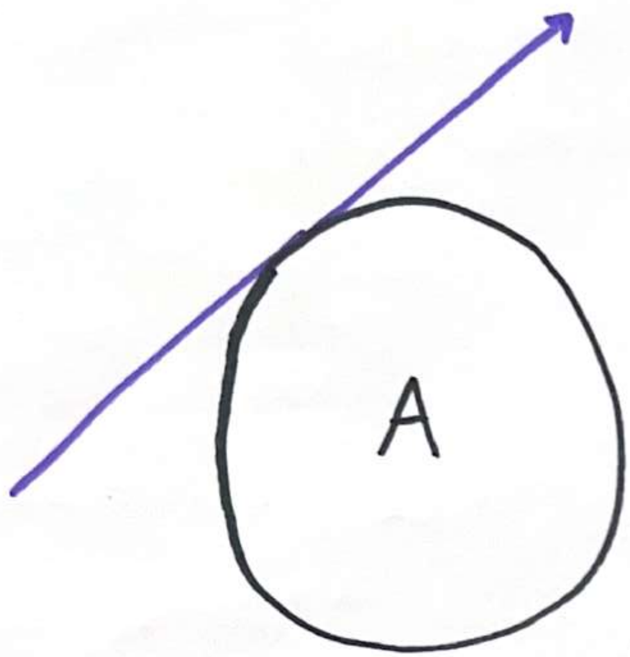
Pf idea: "Slide-turning"

(Czédli–Stachó, 2016)

Slide-turning.



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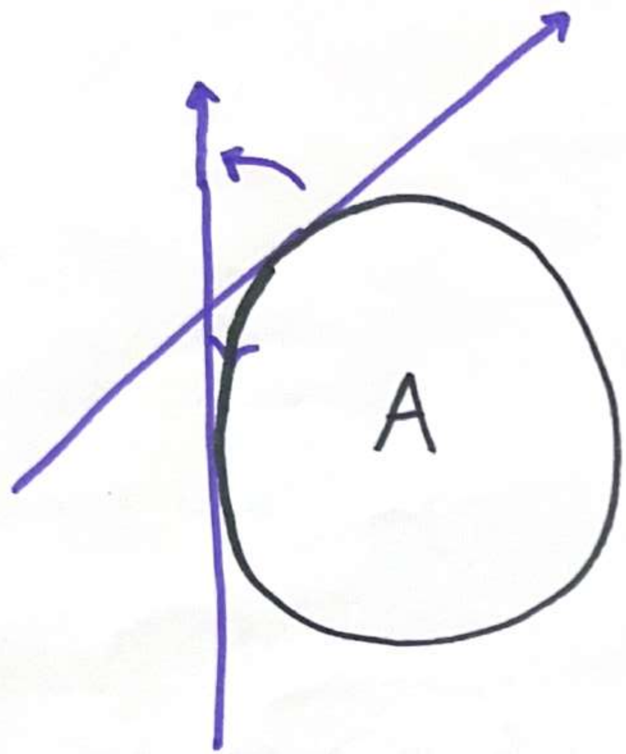

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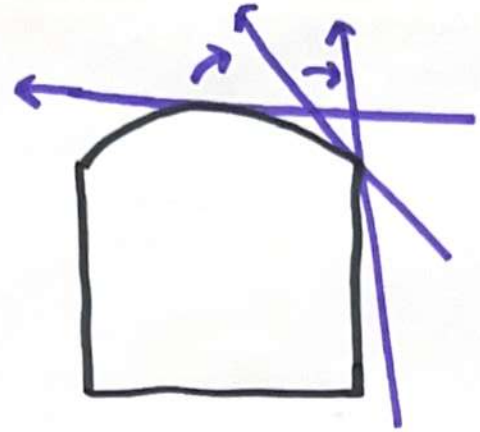

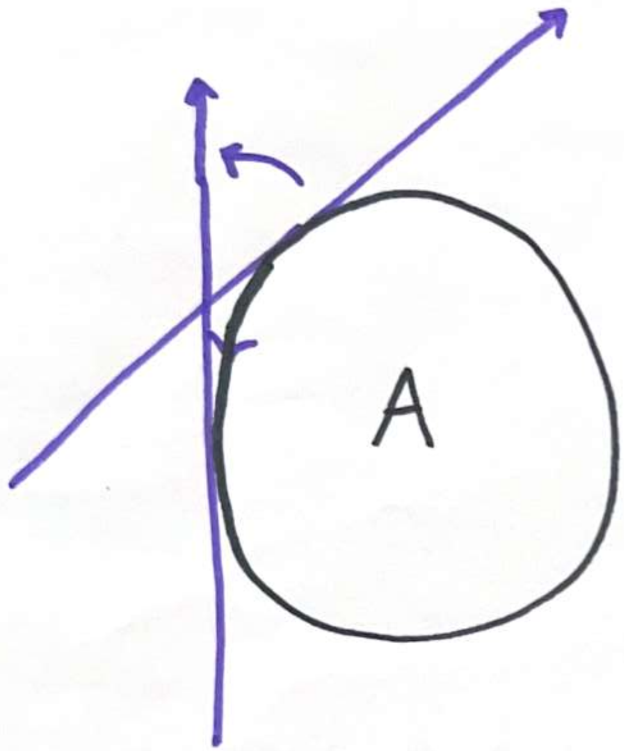

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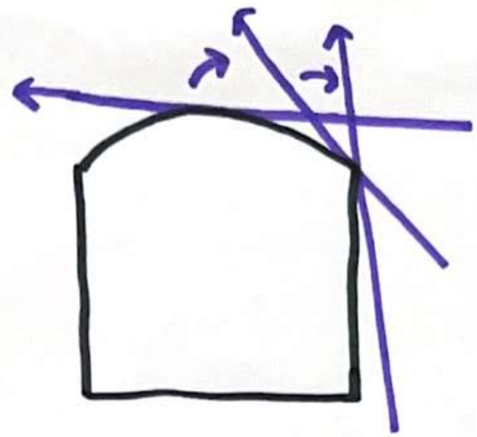

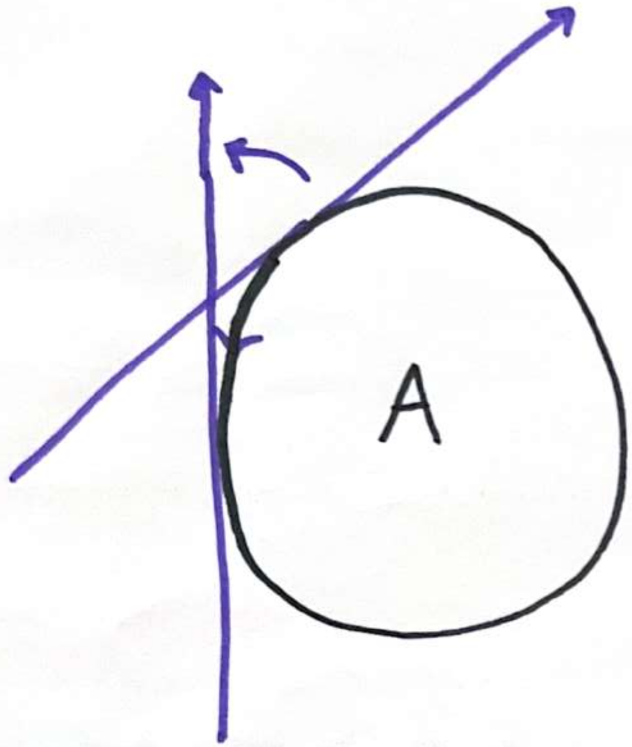

Thm (Czédli – Stachó, 2016).
If A is nonempty, convex, compact, then

$$\left\{ (a,\ell) : a \in \partial A,\ \ell \text{ is a supporting line of } A,\ a \in \ell \right\}$$

is a simple rectifiable curve in $\mathbb{R}^2 \times S^1 \subseteq \mathbb{R}^4$.

Takeaway: We have a bijection

$$[0, 2\pi) \longleftrightarrow \left\{ \begin{array}{c} \text{oriented supporting} \\ \text{lines of } A \end{array} \right\}$$

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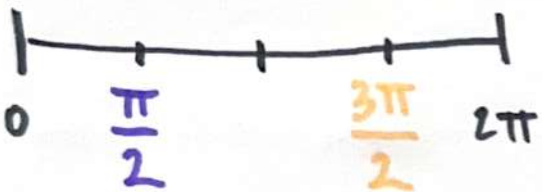

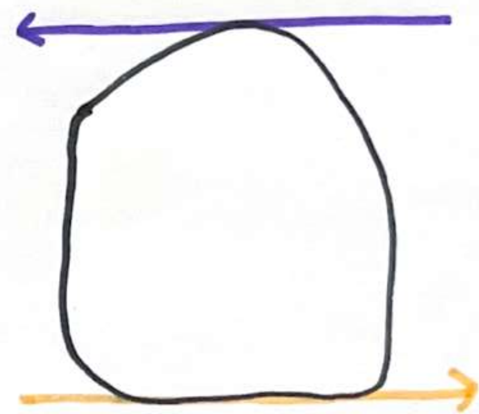

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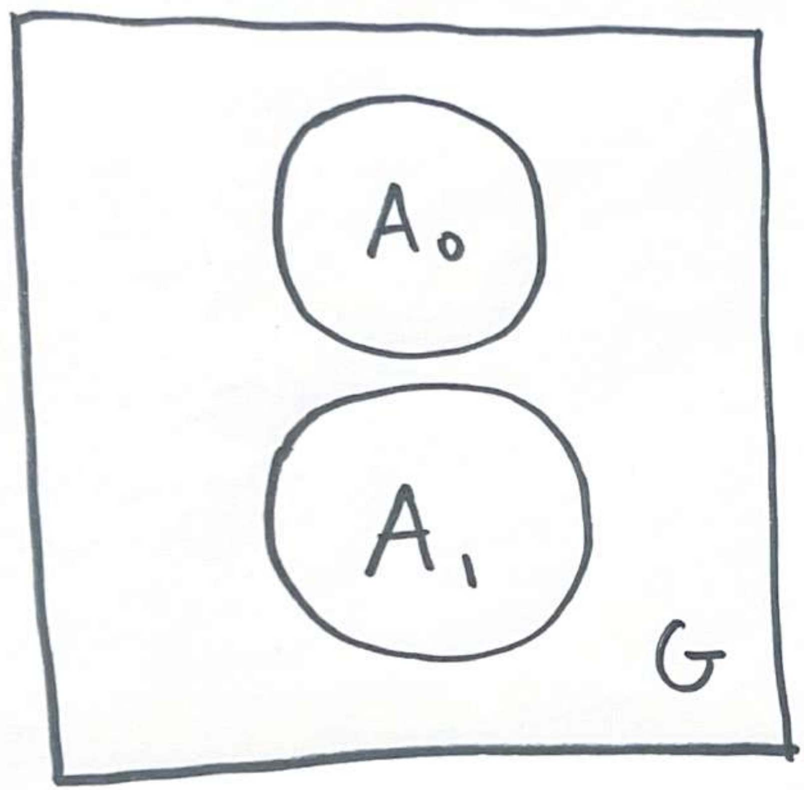

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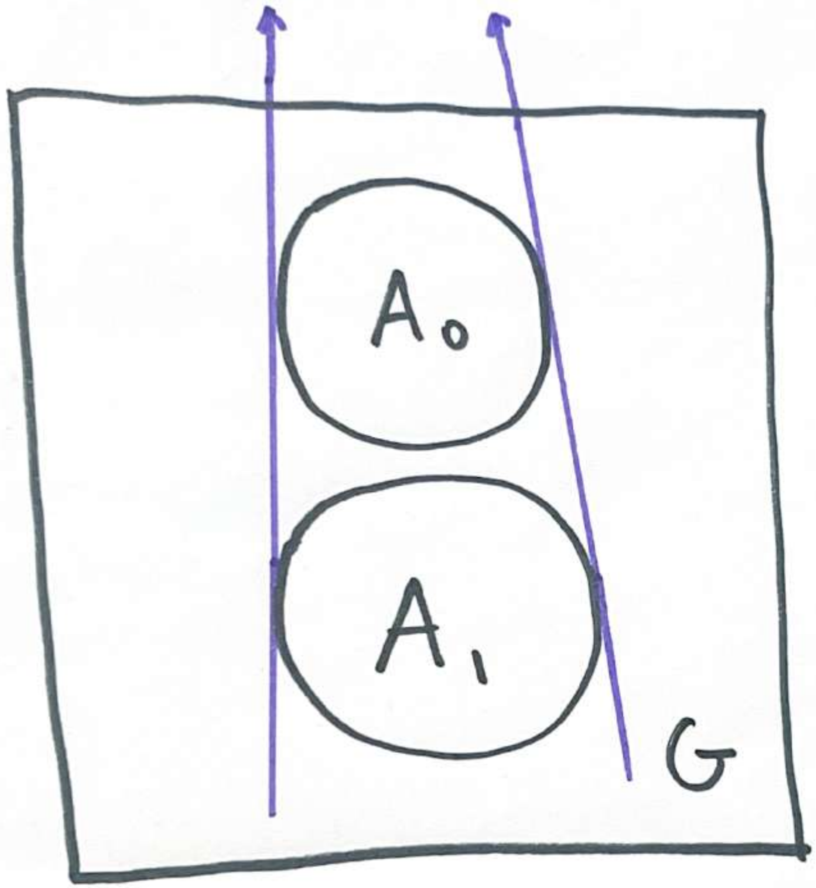

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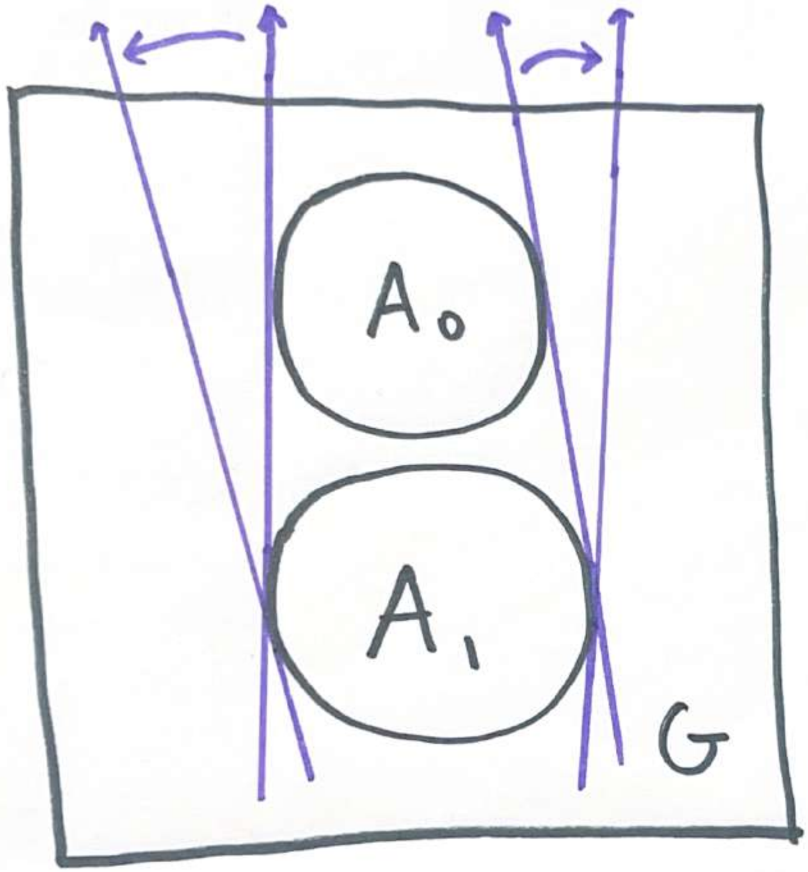

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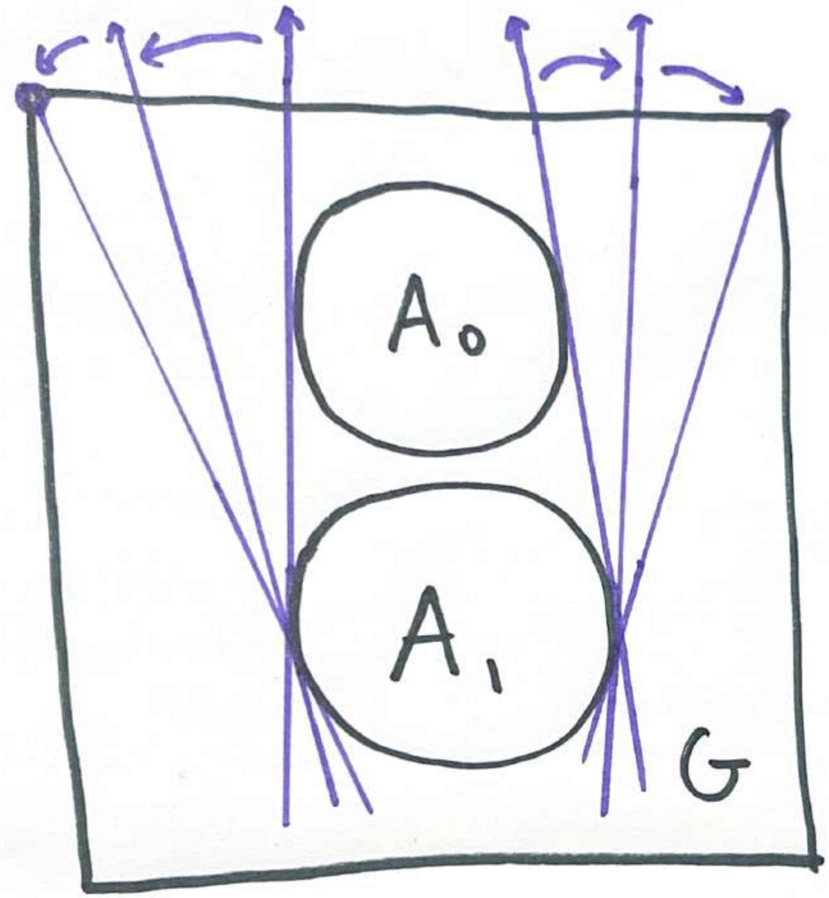

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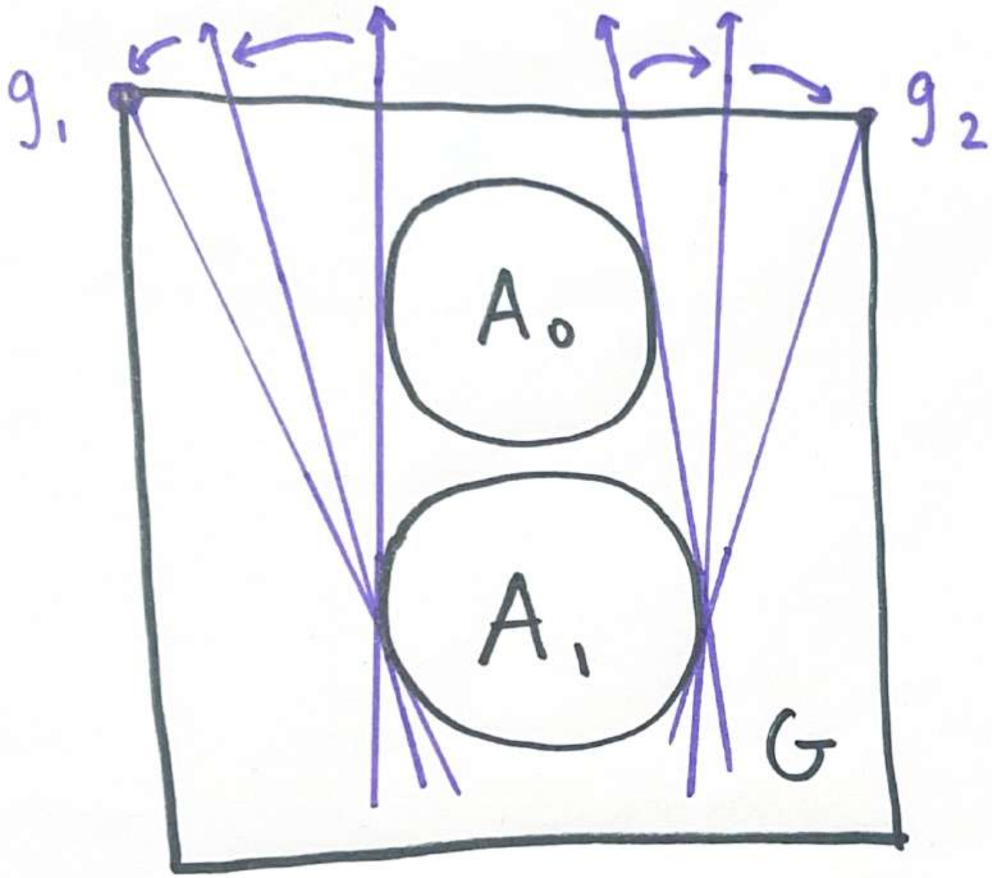
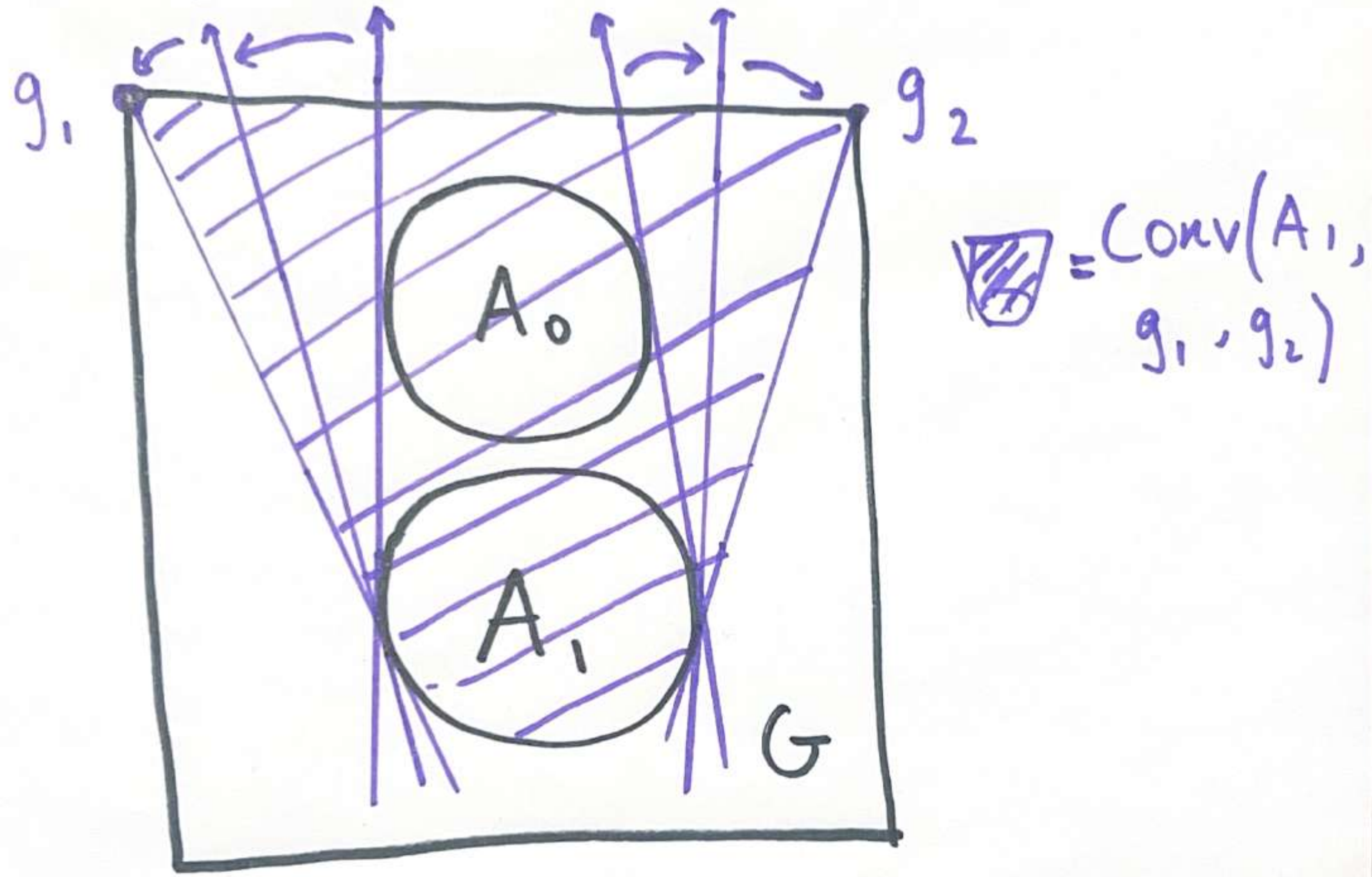


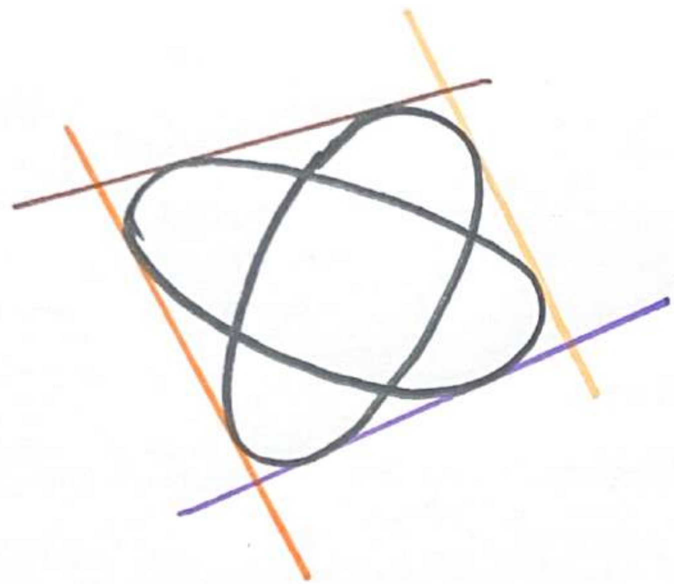
If endpoints of supporting lines intersect vertices of G, we are in luck!

Slide-turning



If endpoints of supporting lines intersect vertices of G, we are in luck!

With multiple supporting lines, each one can slide until the next :



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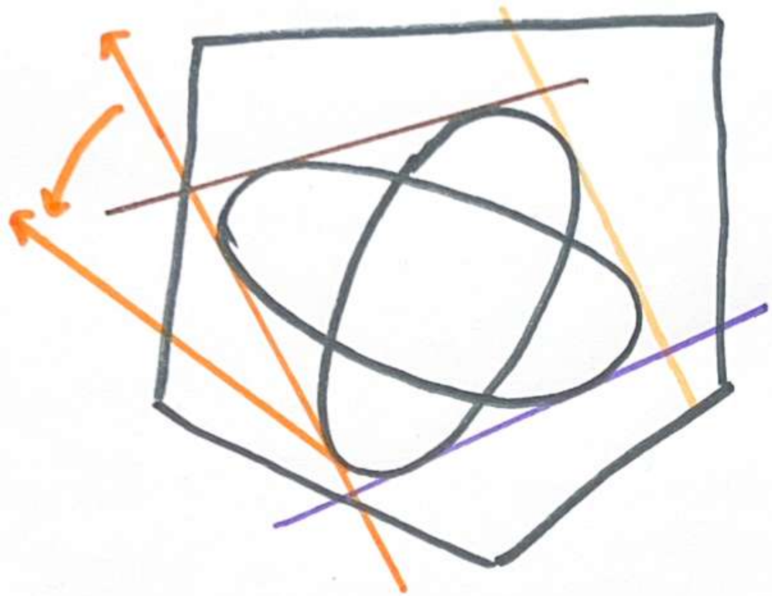

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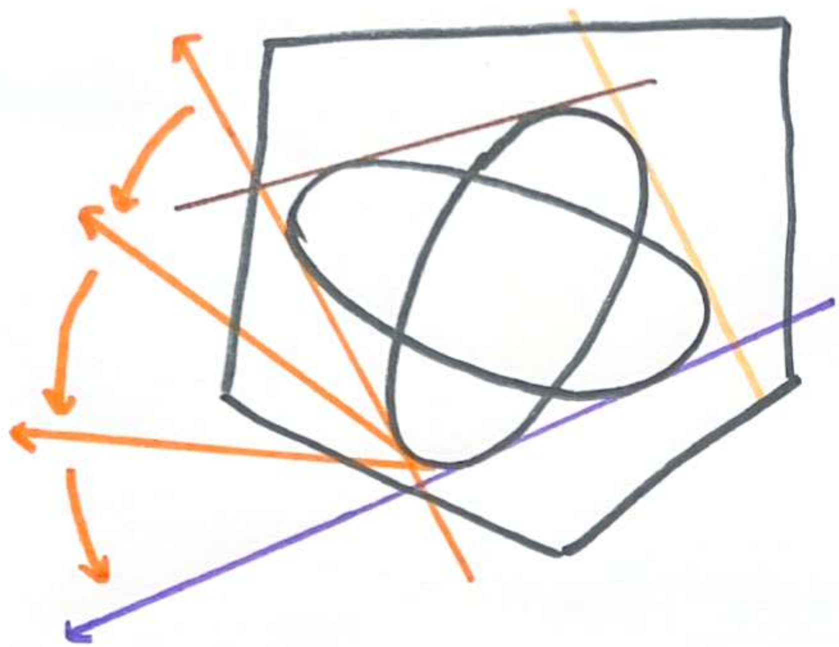

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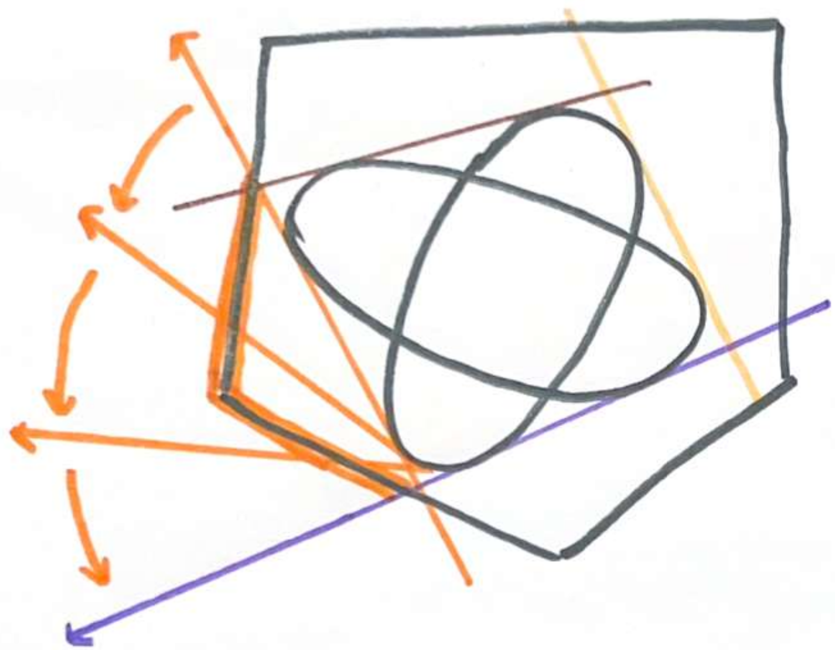

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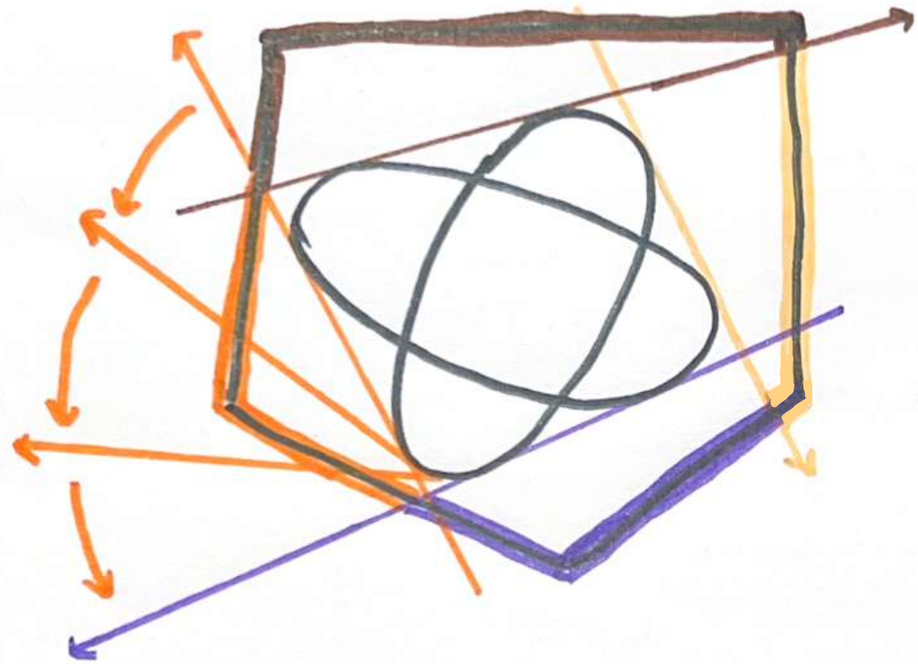

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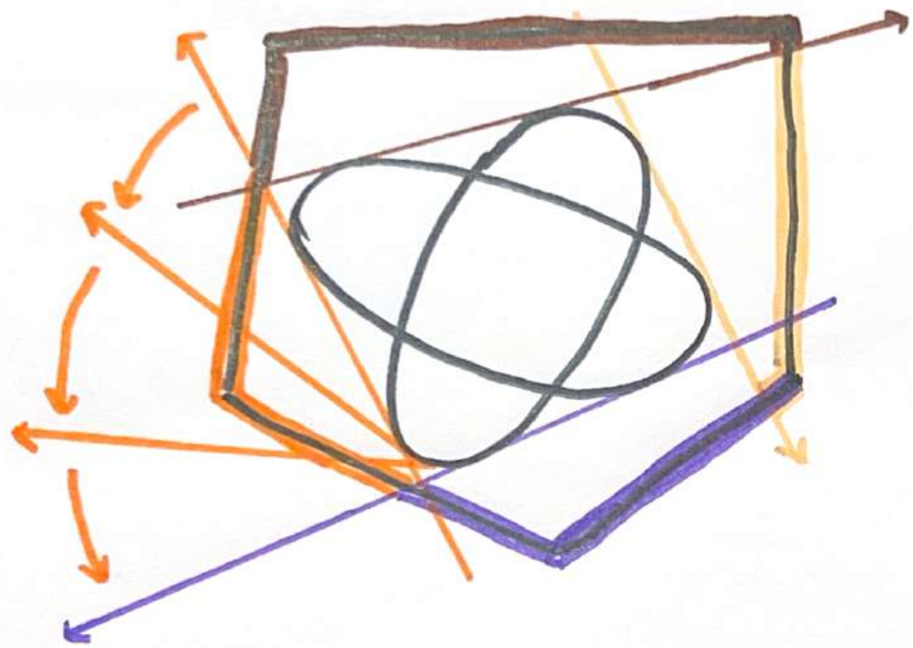
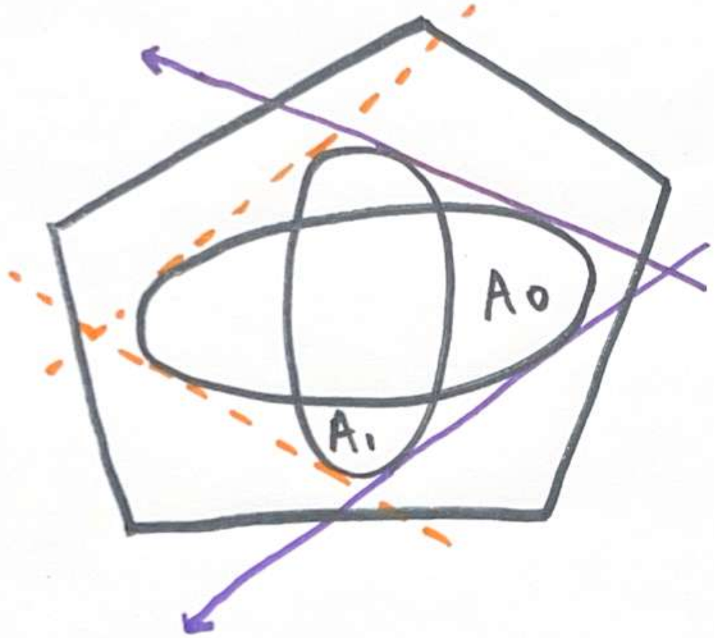


For a fixed orientation, the supporting lines sweep the full boundary of G, hence all vertices.

New goal : Find an <u>adjacent</u> pair of supporting lines that each sweep to a vertex of G.



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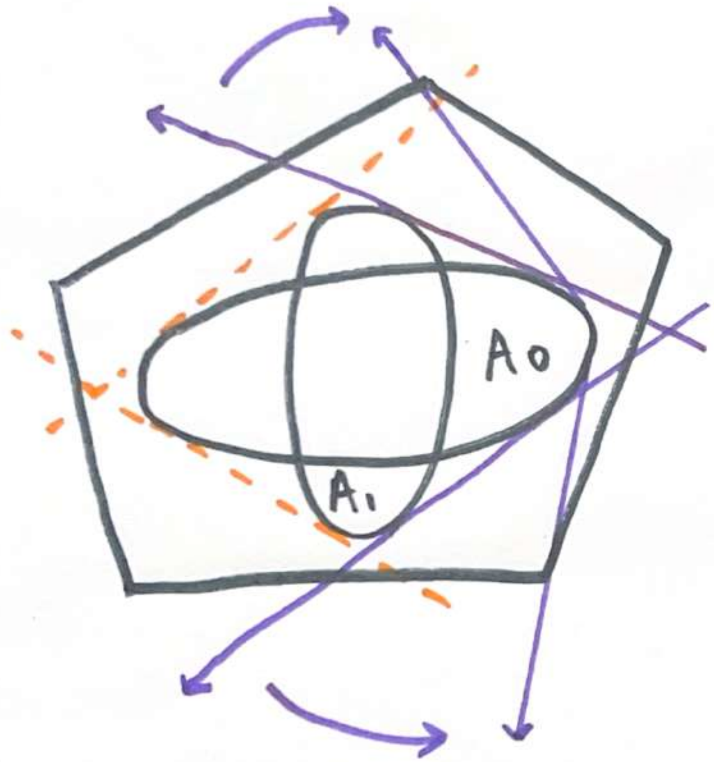

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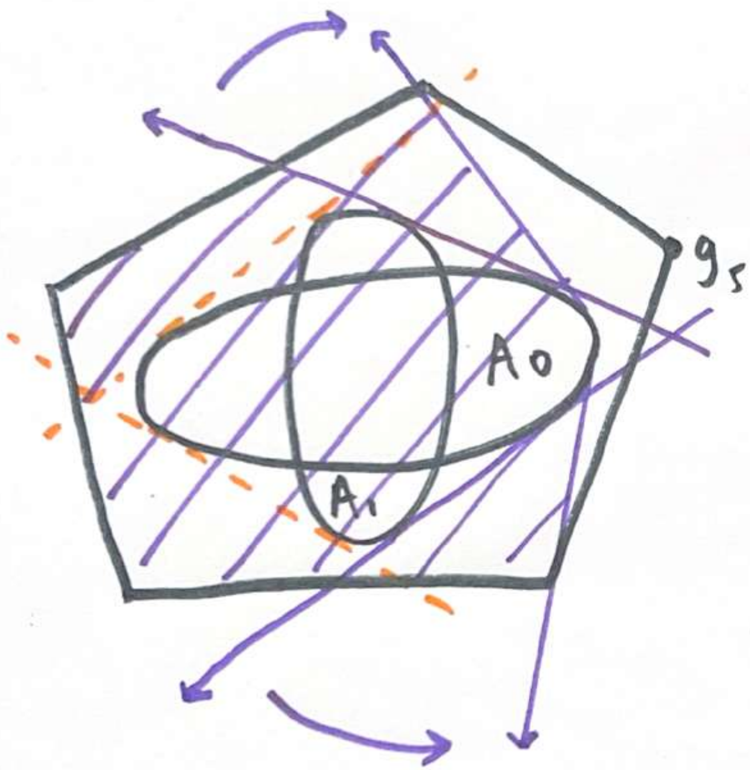
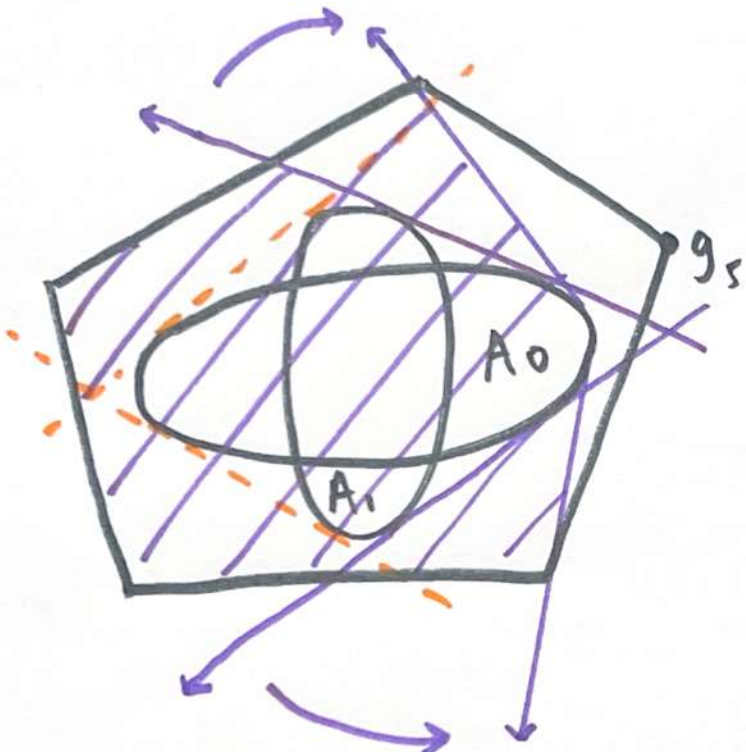


/// : $\mathrm{Conv}(A_0, \{g_1, \dots, g_5\} \setminus \{g_5\})$

New goal: Find an adjacent pair of supporting lines that each sweep to a vertex of G.



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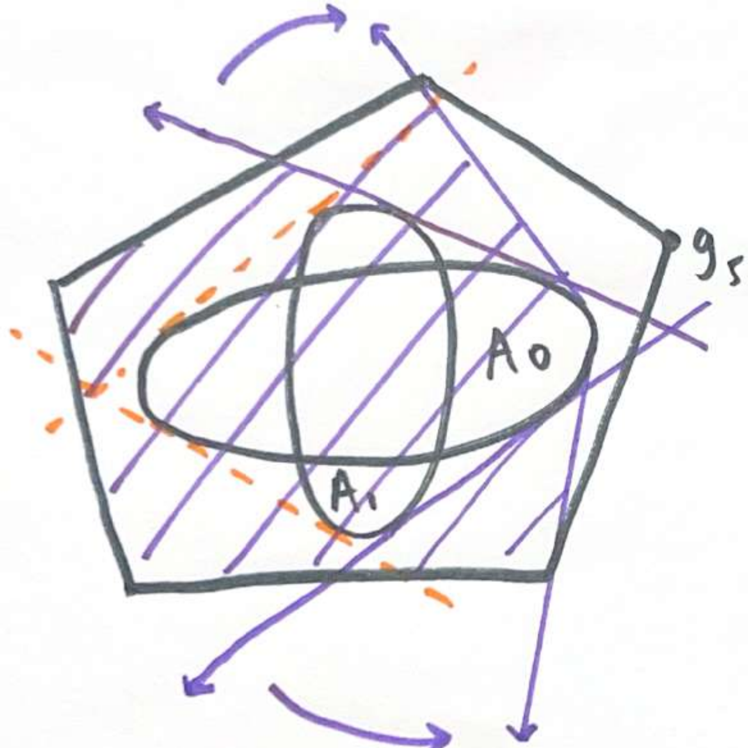
If $\#\left\{\begin{matrix}\text{common supporting} \\ \text{lines}\end{matrix}\right\} < \#\{\text{vertices of } G\}$, these always exist.

New goal : Find an <u>adjacent</u> <u>pair</u> of supporting lines that each sweep to a vertex of G.



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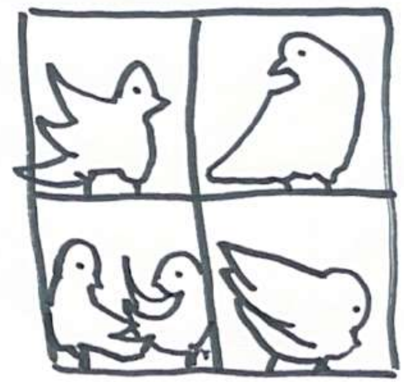

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Cor. $\mathcal{A} = \{A_0, A_1\}$ compact subsets of $\mathbb{R}^2$.
If ∂A_0 and ∂A_1 are smooth plane curves of degree d_1, d_2, and G is a convex n-gon with

$$n > d_1(d_1-1)(d_2-1)d_2,$$

then $(\mathcal{A}, G)$ satisfy the weak carousel rule.

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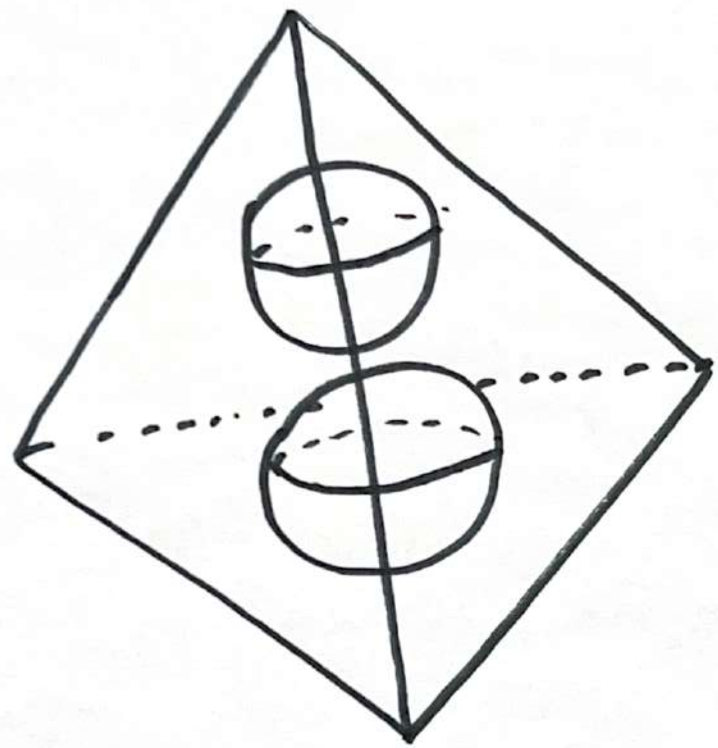
then $(\mathcal{A}, G)$ satisfy the weak carousel rule.

Cor. (Two disks, triangle)

(Two ellipses, pentagon)

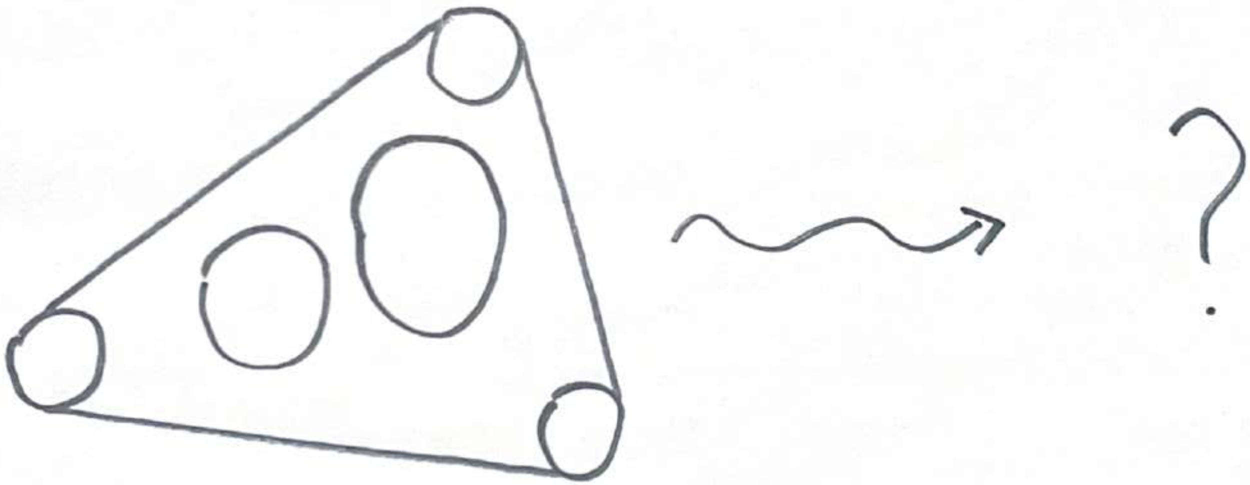
Generalizations fail for $\mathbb{R}^{>2}$.

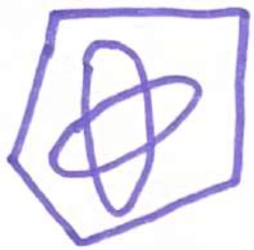


(Czédli, 2017).

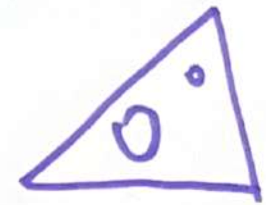
Returning to convex geometries.

Instead of $G = \mathrm{Conv}(\text{points})$, want a theorem for $G = \mathrm{Conv}\left(\begin{smallmatrix}\text{other convex}\\ \text{compact shapes}\end{smallmatrix}\right)$





Thank you!



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