Towards automatic detection of geometric difficulty of geometric problems

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Abstract

We compare three different options to define geometric difficulty C_g of geometry problems.
By computing correlation between the achieved values and the algebraic complexity C_a, and, alternatively, ad-hoc human intuition C_h, we confirm that our former definition seems acceptable.

Why is this interesting?

- Ranking geometry theorems → Wos' Research Problem 31 (1988): *What properties can be identified to permit an automated reasoning program to find new and interesting theorems, as opposed to proving conjectured theorems?* Also studied e.g. by Colton, Bundy and Walsh; Puzis, Gao and Sutcliffe; Gao, Goto and Cheng; Gao, Li and Cheng; and Quaresma, Graziani and Nicoletti.
- Abar and de Almeida: research among university students to learn their personal opinions on geometric difficulty, classifying complexity *before* and *after* attempting to actually prove the statements.
- Algebraic complexity may be different from human perception and geometric complexities → a good measure that works in general? Having such a measure would help to classify problem setting in classroom situations, exams, or mathematics contests.
- Generating new geometry problems → automated estimation of complexity.

Possible definitions of complexity

Algebraic, Z.K., T. Recio and M. P. Vélez, 2023

Let C be a geometric construction with hypotheses H_1, H_2, ..., H_r and thesis T. Prove the statement

$$H_1 \ \wedge \ H_2 \ \wedge \ \ldots \ \wedge \ H_r \Rightarrow T$$

by considering an algebraic proof

$$1 = f_1 h_1 + f_2 h_2 + \ldots + f_r h_r + f_{r+1} \cdot (zt - 1)$$

of the statement, where $h_1, h_2, \ldots, h_r$ are algebraic translations of hypotheses H_1, H_2, ..., H_r, and t is an algebraic translation of thesis T. Then, the *algebraic complexity* C_a of the statement is the maximal degree of f_r, that is

$$C_a := \max_{i=1}^{r+1} \deg f_i.$$

Possible definitions of complexity

Geometric, S. Bartha, A.K., Z.K. and T. Recio, 2024

Let C be a geometric construction with hypotheses $H_1, H_2, \ldots, H_r$ and thesis T. Prove the statement

$$H_1 \ \wedge \ H_2 \ \wedge \ \ldots \ \wedge \ H_r \Rightarrow T$$

by using the Geometric Deductive Database method (GDD) in Java Geometry Expert and consider the number of steps of the proofs, exported as a directed acyclic graph in GraphViz format. Then, the *geometric complexity* C_g of the statement is the number of steps (technically, the *number of lines*) in the output.

Possible definitions of complexity

Geometric (3 variations), A.K., Z.K., present contribution

Let C be a geometric construction with hypotheses $H_1, H_2, \ldots, H_r$ and thesis T. Prove the statement

$$H_1 \ \wedge \ H_2 \ \wedge \ \ldots \ \wedge \ H_r \Rightarrow T$$

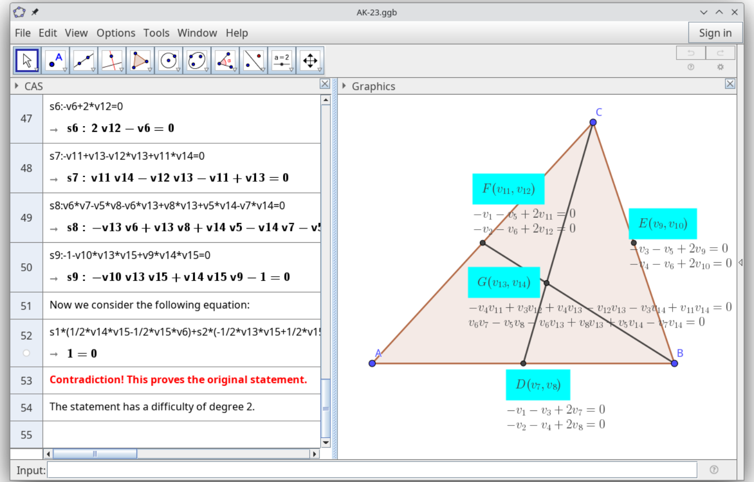
by using the Geometric Deductive Database method (GDD) in Java Geometry Expert and consider the following:

- longest directed path ("Ldp"),
- number of vertices ("#v"),
- number of edges ("#e")

of the obtained directed acyclic graph.

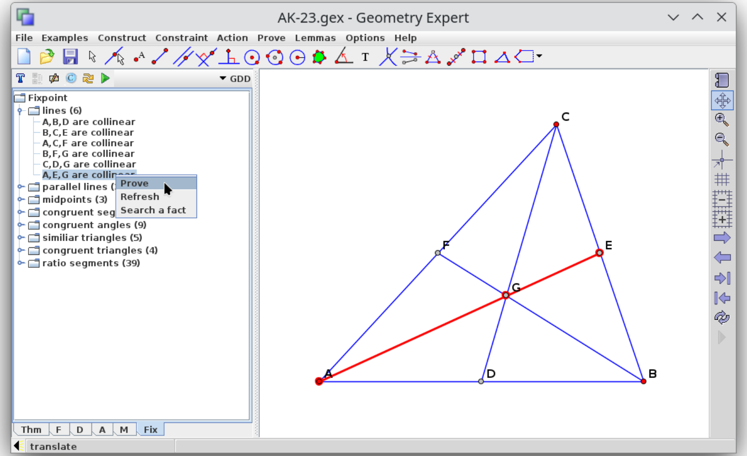
A simple example

Medians of a triangle intersect each other in one point, algebraic complexity (GD), $C_a = 2$



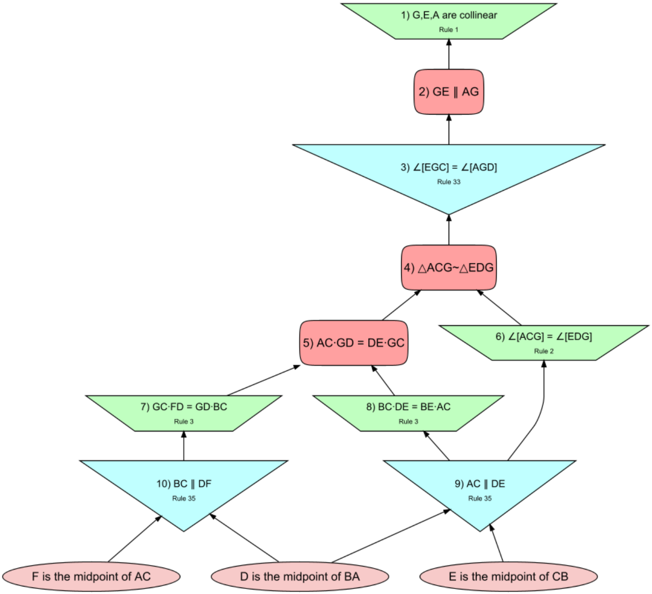
A simple example

Medians of a triangle intersect each other in one point (JGEX)



A simple example

Medians of a triangle intersect each other in one point, geometric complexities



$C_g = 43$
Ldp = 7
#v = 13
#e = 14

A simple example

Computing C_g by counting the lines of the GraphViz output for the GDD proof

```
AK-23.gv          [----]  1 L:[  1+42  43/ 44] *(4312/4313b) 0010 0x00A
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Setting up a database of geometric constructions

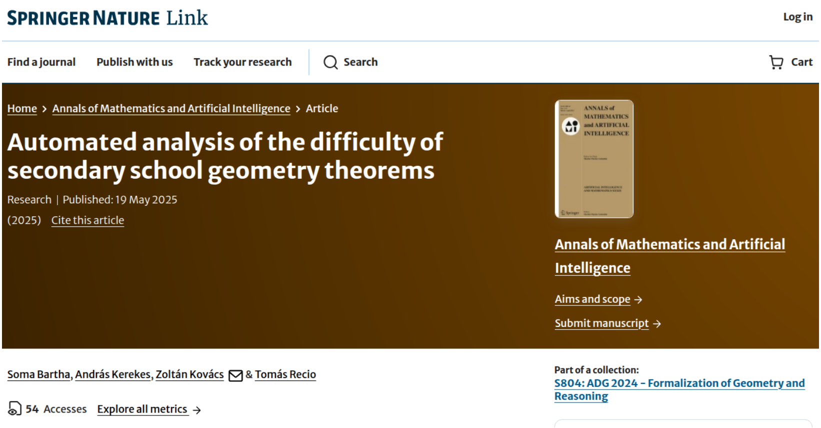
Database of GeoGebra files, joint work with Soma Bartha, June 2024, Linz, Austria

Setting up a database of geometric constructions

Discussion, joint work with Tomás Recio, February 2025, Madrid, Spain

Setting up a database of geometric constructions

Joint work with S. Bartha and T. Recio, published in May 2025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Automated analysis of the difficulty of secondary school geometry theorems

Research | Published: 19 May 2025

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S804: ADG 2024 – Formalization of Geometry and Reasoning

Setting up a database of geometric constructions

Joint work with S. Bartha and T. Recio, published in May 2025

Abstract
We elaborate, as a benchmark, a list of geometry theorems that are regularly used in Hungarian high schools, in specialized tracks for mathematics. Then, these statements are implemented as GeoGebra files, and algebraically proven (with certification) in GeoGebra Discovery. Next, these files are imported in Java Geometry Expert (JGEX), and geometrically proven with the associated Geometry Deductive Database method. In both programs, through quite different approaches in each case, we define and implement an algorithmic measure of the difficulty of a geometric theorem. Then, we compute the corresponding measures on the selected list of statements, and we analyze the obtained collection of pairs of difficulty grades, finding a moderate positive correlation (0.51) between GeoGebra Discovery's algebraic, and JGEX's deductive difficulty formulations. A correlation that seems to support the adequacy of the chosen approximation in our on-going work to algorithmically establish some *ad-hoc* measure of the difficulty of geometric statements that could be reasonably coincidental with the appreciation of human expert users (e.g. teachers).

Keywords Automated theorem prover · Algebraic methods · Deductive Database · GeoGebra Discovery · Java Geometry Expert · Euclidean Geometry

Comparison of difficulty of 14 classroom problems

Theorem	C_a	C_g	C_h	Ldp	#v	#e
Thales' $\bigcirc$ thm	4	13	2.1	2	4	3
Converse of Thales' $\bigcirc$ thm	4	13	2.1	1	3	2
Midline thm	2	10		1	3	2
Intercept thm	7	8	3.4	1	2	1
Theorem of inscr. $\angle$ in a $\bigcirc$	7		3.2	1	2	1
$\angle$ of cyclic quadrilaterals			3.2	1	2	1
Rel. betw. inscr. $\angle$ and $\angle$ at the $\odot$			3.2	2	5	4
Tangent-secant thm	6	16	3.8	3	5	4
Wallace-Simson thm	16	53	4.8	8	20	19
Euler's line	7	120	5.4	11	34	46
9-point $\bigcirc$	18	94	5	5	23	32
Circumcenter of a $\triangle$	2	25		3	9	8
Barycenter of a $\triangle$	5	43		5	9	10
Apollonius' thm	7		3.2	5	12	11

Results of the questionnaire

C_h is taken as the average of the answers (line 13), stddev is shown in line 14

Matematikai tételek nehézsége (v2) (válaszok) előadáshoz

Form_Responses1

	A	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
1	Időbélyeg	Thálesz-tétel és megfordítása	Pitagorasz-tétel és megfordítása	Héron-képlet	Háromszög-egyenlőtlenség	Nagyobb szöggel szemben nagyobb oldal van	Ceva-tétel és megfordítása	Menelaosz-tétel és megfordítása	A párhuzamos szelők és szelőszakaszok tétele	Szögfelező-tétel	Derékszögű háromszög magasságtétele	Befogótétel	Kerületi- és középponti szögek tétele	Húrnégyszögtétel	Külső pontból húzott érintőszakasz hossza egyenlő a pontból húzott szelőszakaszok mértani közepével	Metsző húrok darabjainak szorzata egyenlő	Ptolemaiosz-tétel	Euler-egyenes	Feuerbach-kör	Wallace–Simson egyenes tétele	A háromszög trigonometrikus területképlete	Szinusztétel	Koszinusztétel
2	2025.02.12. 15:28:40	1	1	2	1	2			4	4	1	2	4	5	5			7			5	2	1
3	2025.02.12. 15:30:08	1	1	3	1	1	?	?	1	1	1	1	1	1	1	?	?	3	3	?	1	1	1
4	2025.02.12. 15:34:48	3	3	4	4	4	6	6	2	3	3	3	3	4	4	4	7	5	5	6	4	4	4
5	2025.02.12. 15:37:44	1	1	3	2	2	4	4	4	4	4	3	3	2	3	4	4	5	5	5	4	4	4
6	2025.02.12. 15:38:12	3	3	4	1	2	4	4	2	4	5	4	3	5	5	5	4	6	5	7	5	5	4
7	2025.02.12. 15:56:32	2	2	3	3	5			4	4	3	3	3	3	6	6			6				
8	2025.02.12. 16:40:25	1	2	2	1	1	4	4	2	3	3	3	3	3	3	3	5	5	4	3	3	3	3
9	2025.02.12. 17:30:27	2	2	4	1	1			2	2	1	1	3	2	2	2	2	4	5	3	2	3	3
10	2025.02.12. 18:22:31	3	3	4	2	4	6	6	5	5	4	5	5	5	5	5	6	6	5		5	5	5
11	2025.02.12. 22:11:38	1	1	4	3	1	4	4	3	2	2	2	2	2	1	3	3	5	4	5	3	2	2
12	2025.02.17. 17:35:23	5	4	5	4	5	6	7	8	3	3	4	5	3	2	2	9	8	8		5	5	5
13	Átlag	2,09	2,09	3,45	2,09	2,55	4,86	5,00	3,36	3,18	2,73	2,82	3,18	3,18	3,36	3,78	5,00	5,40	5,00	4,83	3,70	3,40	3,20
14	Szórás	1,24	1,00	0,89	1,16	1,56	0,99	1,20	1,87	1,11	1,29	1,19	0,99	1,34	1,67	1,31	2,12	1,36	1,26	1,46	1,35	1,36	1,40
15																							

A.K.'s classmates

Some of them participated in filling in a questionnaire

Correlation computations

	C_g	C_h	Ldp	#v	#e
C_a	0.58	0.71	0.47	0.57	0.54
C_g		0.84	0.88	0.98	0.99
C_h			0.81	0.86	0.85
Ldp				0.94	0.90
#v					0.99

The correlation computation was performed via Pearson's correlation formula for samples,

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

where n is the sample size, and x_i and y_i are the individual sample points indexed with i, $1 \leq i \leq n$, moreover, $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$ is the mean for sample points $x_1, \ldots, x_n$, the same for $\bar{y}$, respectively.

Conclusion and future work

- $C_g \sim C_a$ is the closest geometric complexity.
- #v and #e are very close to C_g.
- C_h is, surprisingly, between C_a and C_g.
- Both the amount of theorems and the number of participants in the questionnaire are quite low. The research should be therefore repeated
  - in the same school, in different classes of young learners,
  - in other Hungarian schools, in special math program classes,
  - in other countries,

  to work on a larger dataset.
- C_a could be defined differently, e.g. by taking the maximal number of terms in the f_i in the formula

$$1 = f_1 h_1 + f_2 h_2 + \ldots + f_r h_r + f_{r+1} \cdot (zt - 1).$$

THANK YOU!

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