

Creating Realistic 3D Graphics with Excel at High School – Vector Algebra in Practice

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Abstract. The article presents the results of an experiment in which Excel applications that depict rotatable and sizable orthographic projection of simple 3D figures with face overlapping were developed with thirty gymnasium (high school) students of age 17–19 as an introduction to 3D computer graphics. A questionnaire survey was conducted to find out whether the students acquired the principles of the projection, found the lessons interesting and contributing to their technological knowledge, and found the topic motivating enough to continue with more complicated models. The results are discussed.

Keywords: face overlapping, orthographic projection, spreadsheets, virtual reality.

1. Introduction

Virtual reality technology has become the part of everyday life. It is used in games, films, and in education at all levels (Albin-Clark *et al.*, 2011; Huleihil and Huleihil, 2011; Kartiko *et al.*, 2010). Research proves that applying virtual reality based instruction results in better visual comprehension, statistically significant higher intrinsic motivations and effective enhancing students' achievement (Mintz *et al.*, 2001; Kwon and Kim, 2002; Cooper *et al.*, 2003; Costa *et al.*, 2006; Garrett and McMahon, 2010; Mikropoulos and Natsis, 2011).

Virtual reality technology applies mainly the central projection, in which the lines that are parallel in reality are depicted as intersecting in the distance. That is how humans see the world (see e.g. Benacka, 2012). However, the feature obscures the relations among the objects and makes the projection inappropriate to STEM disciplines and mathematical educational software. Instead, the parallel projection is used, which depicts parallels as parallels (Benacka, 2008, 2011a, 2011b; Cabri 3D, n.d.; Tambade, 2011; Wu and Chiang, 2013).

The author (Benacka, 2013) presented a method of explaining the principles of 3D graphics through making a rotatable and sizable orthographic projection of cuboid in Excel® in a 90 minute lesson. The lesson was taught to 181 participants including 34 gymnasium (high school, age 15–19) students. The main result of the questionnaires given to the participants was that they all found the lesson interesting, and 82% of the gymnasium students would have liked to continue and include face overlapping into the application to make it more realistic. That was 92% of those students who developed the application in optional informatics lessons, that is, who were interested in informatics.

This article presents the results of an experiment in which Excel applications that depict rotatable and sizable orthographic projection of simple 3D figures, cuboid and tower consisting of cuboid and pyramid, with face overlapping were developed with 30 gymnasium students in two 90 minute optional informatics lessons as an introduction to realistic 3D graphics in the sense of synthesizing computing, STEM and real life (Wiechers, 1974; Knuth, 1974, 1985; Microsoft, 2005; Stephenson *et al.*, 2005; European Commission, 2010; U.S. Department of Education, 2010; Ruiz Jimenez and Ruiz Muñoz, 2011; The White House, 2013). The first factor that motivated the choice of the activities that the paper deals with was the feedback from author's teaching at university and gymnasium that many students, when working with 3D software (see e.g. O'Shea *et al.*, 2009; Stowell *et al.*, 2009; Quick *et al.*, 2012), are interested in how 3D figures are depicted on the screen. The second motivating factor was the author's finding that the problem of face overlapping is of great interest to students interested in informatics. In that sense, the paper is a follow up to the author's paper mentioned above (Benacka, 2013). The potential cognitive impact was not only acquiring the principles of realistic 3D computer graphics but also gaining a non-traditional look at vector algebra as a tool to find out whether a face of a non-transparent 3D figure is visible or not – a real problems that have nothing with vectors at first sight.

The teaching process was carefully planned with the key point to prepare learner centred lessons with concept-based approach (Hadjjerrouit, 2008, 2009). Standard spreadsheet functions were used in the applications, that is, no VBA programming skills were required. A questionnaire survey was conducted to find out whether the students acquired the principles of the projection, found the lessons interesting and contributing to their technological knowledge, and found the topic motivating enough to continue with adding colours and depicting more complicated figures. The results are discussed.

2. Orthographic Projection

Let the orthonormal coordinate system $O'x'y'$ be defined in plane ρ . Let plane ρ be placed in the orthonormal right-handed coordinate system $Oxyz$ so that $O \notin \rho$, $OO' \perp \rho$, $|OO'|=1$, and $x' \parallel xy$. Let the position be given by angles ϕ and θ according to Fig. 1. The intersection point of plane ρ and the line going through point $A(x, y, z)$ parallel to OO' is the orthographic projection $A'(x', y')$ of point A onto plane ρ and it holds that (Benacka, 2008)

$$x' = -x \sin \phi + y \cos \phi, \tag{1}$$

$$y' = -x \sin \theta \cos \phi - y \sin \theta \sin \phi + z \cos \theta, \tag{2}$$

where $-180^\circ \leq \phi \leq 180^\circ$ and $-90^\circ \leq \theta \leq 90^\circ$.

Plane ρ is the projection plane and vector $\mathbf{s} = OO' = (\cos \theta \cos \phi, \cos \theta \sin \phi, \sin \theta)$ is the projection vector.

3. Problem of Face Overlapping

Let a non-transparent cuboid $ABCDEFGH$ of edge lengths a , b and c be placed in the $Oxyz$ coordinate system so that its centre is at origin O and the faces are parallel to the coordinate planes (Fig. 2). The coordinates of the vertices are $(\pm a/2, \pm b/2, \pm c/2)$ taking + or -.

It holds for a visible face that the angle between the normal vector to the face and the projection vector is acute. Then, the scalar product of the two vectors is positive. On that condition, the face has to be drawn otherwise not. Therefore, the projection of the cuboid is drawn by faces. Each face is drawn as a XY line graph going through the

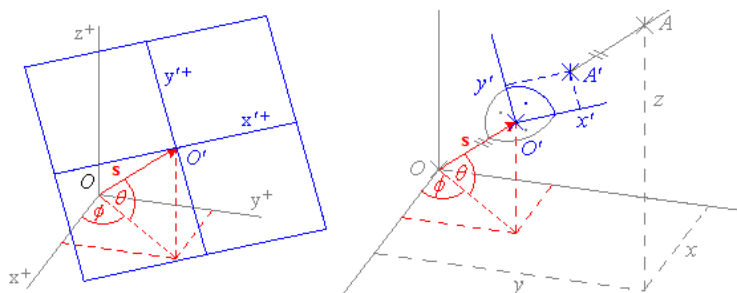


Fig. 1. Projection plane in the $Oxyz$ coordinate system (left) and the orthographic projection $A'(x', y')$ of point $A(x, y, z)$ in the $Ox'y'$ coordinate system (right).

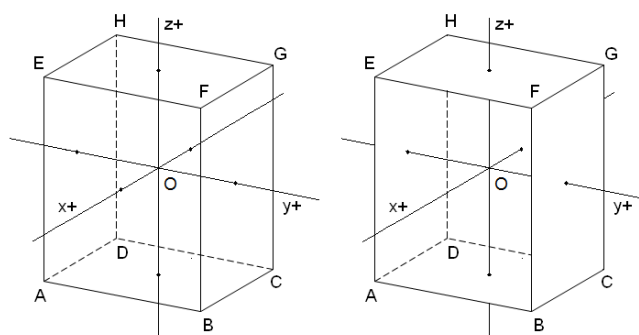


Fig. 2. Cuboid in the $Oxyz$ coordinate system (left) and the model with one face missing (right)

vertices of the face in anticlockwise succession. The last vertex equals the first one to produce a closed shape. The normal vectors to the faces are:

$$(1,0,0), (-1,0,0), (0,1,0), (0,-1,0), (0,0,1) \text{ and } (0,0,-1).$$

The normal vector to a generally positioned face has to be calculated as the vector product of two non-collinear vectors lying in the face, e.g. the one that goes from the first vertex of the face to the second one, and the one that goes from the first vertex to the third one.

4. Applications

The Cuboid application is in Fig. 3. The grey cells contain formulas. Cells C4, C5, C6, AA2 and AA3 are renamed *a*, *b*, *cc*, *fi* and *th* (a cell cannot be renamed *c*).

Scrollbar properties LinkedCell are set to AA5 and AA6, Min to 0, Max to 360 and 180, SmallChange to 1, and LargeChange to 5. That makes ϕ go from -180° to 180° by 1° or 5° and θ from -90° to 90° by 1° or 5° . The coordinates of the projection vector are in range C9:E9. The coordinates of the vertices are in range C12:E19. Range B12:E19 is renamed *vertices*. The base face is processed in range B22:G28. The coordinates of the normal vector are in range C22:E22. Cells C24:E28 contain formulas that give the *x*, *y*, *z* coordinates of the vertices. The scalar product of the normal and projection vector is in cell G22. Cells F24:G28 contain formulas that give the *x'*, *y'* coordinates of the vertices if the value in cell G22 is not negative; otherwise they give 0, which causes the face to collapse in the point $(0,0,0)$.

Range C22:G28 is used as a template for the other five faces. The formula from cell G22 is copied in cell AB22 and so on for the other faces. Then, absolute address $\$G\22 in the formulas in cells F24:G28 is changed to relative G22 (that is why it is in **bold** in Table 1), and range C24:G28 is copied and pasted in range X24:AB28 and so

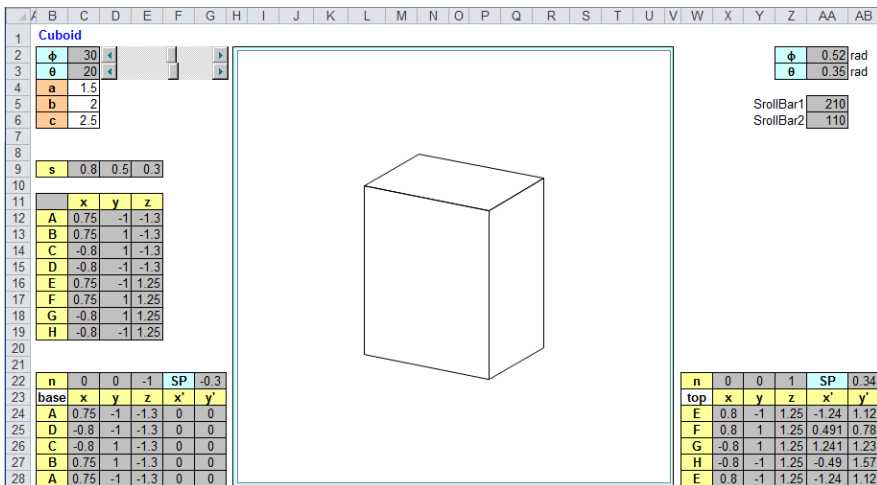


Fig. 3. Orthographic projection of a cuboid with face overlapping.

Table 1
Formulas used in the Cuboid application

C2	=AA5-180	C22	=0
C3	=AA6-90	D22	=0
AA2	=RADIANS(C2)	E22	=-1
AA3	=RADIANS(C3)	G22	=SUMPRODUCT(s;C22:E22)
C9	=COS(AA3)*COS(AA2)	C24	=VLOOKUP(B24;vertices;2) →C28
D9	=COS(AA3)*SIN(AA2)	D24	=VLOOKUP(B24;vertices;3) →C28
E9	=SIN(AA3)	E24	=VLOOKUP(B24;vertices;4) →C28
C12	=a/2 →C19 (+ or -)	F24	=IF(\$G\$22<0;0;-C24*SIN(fi)+D24*COS(fi)) →C28
D12	=-b/2 →D19 (+ or -)	G24	=IF(\$G\$22<0;0;-C24*SIN(th)*COS(fi)- D24*SIN(th)*SIN(fi)+E24*COS(th)) →C28
E12	=-cc/2 →E19 (+ or -)		

on for the other five faces. The chart is of type XY. It comprises six graphs made over range F24:G28 for the base face and so on for the other five faces. The minimum and maximum of the axes are set to -3 and 3 . The axes are hidden. The formulas used in the application are listed in Table 1. Notation \rightarrow C19 means that the formula is filled down as far as cell C19.

The Tower application is in Fig. 4. It is based on the Cuboid application. Range W22:AB28 is deleted and the top face is cleared away from the chart. Range B7:C7 is added for the height of the roof. Cell C7 is named h . Range B20:E20 is added for the coordinates of the apex of the roof. Range B38:G45 is added for the front face of the roof and so on for the others roof faces. The coordinates of two non-collinear vectors that lie in the roof front face are calculated in cells C38:E39. The coordinates of the normal vector are calculated in cells C40:E40. The formulas from cell G22 and C24:G27 are copied and pasted in cells G40 and C42:G45. Four other graphs are added into the chart made over range F42:G45 for the roof front face and so on for the others. The formulas used in the application are listed in Table 2.

5. Population

The experiment was carried out with three groups of gymnasium students, 30 altogether. The first and second group were 8 last year (age 18–19) and 8 last but one year students in optional subject Informatics, which is a follow-up to compulsory subject Informatics taught in the previous years. The third group were 14 last year students in subject Applied Informatics, which is another optional follow-up to compulsory subject Informatics. All students had learned about vectors and scalar and vector product in the previous years. In Excel, they had learned about writing formulas with relative and absolute addresses, using basic statistical functions and function IF, and making bar and pie graphs. They had not learned about using sliders and other components, using functions VLOOKUP, RADIANS, SIN, COS and SUMPRODUCT, renaming cells and making XY graphs.

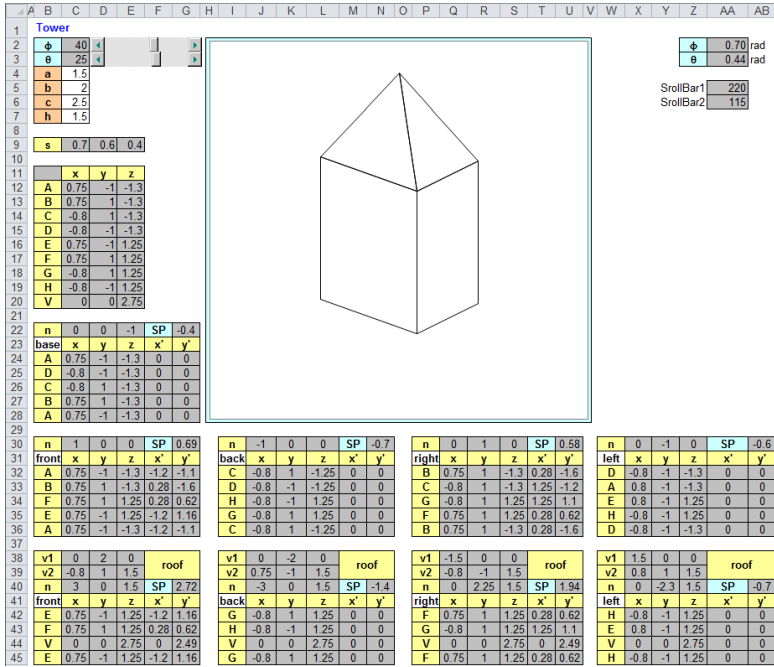


Fig. 4. Orthographic parallel projection of a tower.

Table 2
Formulas used in the application

C20	=0	C39	=C44-C42
D20	=0	D39	=D44-D42
E20	=cc/2+C7	E39	=E44-E42
C38	=C43-C42	C40	=D38*E39-E38*D39
D38	=D43-D42	D40	=E38*C39-C38*E3
E38	=E43-E42	E40	=C38*D39-D38*C39

6. Tools

The principle of the orthographic projection was explained by using the following teaching aids: a transparent plastic sheet for the projection plane, pieces of wire for axes x , y , z and projection lines, and a carton cuboid with faces perforated in the centres and one face missing (Fig. 2). The Cuboid application was developed by using a template, which was the application in Fig. 3 without formulas and chart. Applying a template had two reasons – it fastened developing the application but, mainly, it caused the students’ work to be uniform, which was crucial for checking on the correctness. Each student worked on his/her computer. The teacher worked on his computer and used data projector. The students were not examined thus no assessment tools were used except for questionnaires given at the end of the lessons.

7. Process

The author taught two 90 minute lessons to each group. The Cuboid application was developed in the first lesson, the Tower application was developed in the second lesson.

The **first lesson** started with seeing Forum romanum (n.d.) as it looked like 2000 years ago. Then, students compared paintings “Scenes from the Life of Saint John the Baptist” (n.d.) and “School of Athens” (n.d.). They found the former unrealistic while the latter gave them, due to using perspective, the feeling of watching a real scene through a window. The teacher familiarised the students with perspective and the fact that it was discovered by Italian painters in the 15th century, and that it is the principle on which virtual reality is constructed. The students found that depicting parallel lines as lines intersecting at a point is excellent in art and films but inappropriate for using in engineering and mathematics.

The teacher showed the model depicted in Fig. 2. He drew coordinate system $O'x'y'$ onto the plastic sheet, put a piece of wire perpendicular to the sheet at point O' for the normal vector, and put the system in the $Oxyz$ system as shown in Fig. 1. He demonstrated that changing ϕ from -180° to 180° and θ from -90° to 90° enables one to move the projection plane around the figure. Then, he projected the vertices of the cuboid onto the sheet by using pieces of wire (Fig. 1). He demonstrated that the x', y' coordinates depend on the x, y, z coordinates and angles ϕ and θ , and presented Eq. (1) and Eq. (2).

The teacher presented the application in Fig. 3 through a data projector to motivate. The students downloaded the template from the author’s website and started developing the application. The teacher was developing the application along and projecting it to give feedback but with a delay to enable the clever student work individually.

The teacher posed questions to each steps of the creation until one or more students answered correctly. Then, the participants filled the formulas in the relevant cells. If they were not familiar with the function used, the teacher explained it. The teacher proceeded to the next step only if all students got the same result in the relevant cells. The students were allowed to communicate and compare their work with the others in the class but they did it minimally. Just in the case of a significant time lag was a student given help from the teacher or other students. The Cuboid application was completed in the first lesson except for the scrollbars that were not employed due to lack of time. However, the projection was rotatable by rewriting angles ϕ and θ in cells C2:C6. At the end of the lesson, the application in Fig. 4 was shown for further motivation.

The students filled in the first questionnaire.

The **second lesson** started with revising the first lesson. The scrollbars were added. The ranges for the height, apex and faces of the roof were created. The principle of calculating the coordinates of the normal vector to a roof face was discussed. The application was completed as written in section 4. At the end of the lesson, an application with a coloured house was shown for further motivation.

The students filled in the second questionnaire.

8. Pedagogical remarks

The Cuboid application was developed in four steps to keep the students attention during the lessons. The first step was calculating the vertex coordinates (range C12:E19), the base (C24:G28) without using function IF, that is, ignoring overlapping, and adding the base into the chart. The first hit was when the base appeared in the chart and the student rotated it by rewriting angles ϕ and θ . Seeing that creating the projection was not as complicated as it had seemed, the students got clearly excited and eager to proceed to the second step, which was filling in the formulas for the other faces and adding the faces into the chart. The second hit was when the mesh model of the cuboid appeared in the chart and the student rotated it by rewriting angles ϕ and θ . The third step was including overlapping. Rotating the cuboid so that only the visible faces were depicted was the third hit, which clearly gave the students the feeling of achievement and satisfaction. The fourth step was adding scrollbars to govern angles ϕ and θ . Rotating the cuboid by the scrollbars was the fourth hit, which the students clearly enjoyed. That was the biggest hit in the lessons.

Other two steps were necessary to finish the Tower application. They were deleting the top face and adding the mesh model of the roof, and including the overlapping of the roof faces. While the former step did not give much excitement, the latter was the fifth hit. The students were clearly pleased to have completed the application.

The course of the lessons suggested that, had there be no questionnaire, it would be appropriate to swap steps three and four. The advantage would be that the topic of depicting scrollbar rotatable mesh models of 3D figures would be completed in the first lesson, while the second lesson could be entirely aimed to solve the problem of face overlapping. That was the author's intention; however, due to the need to involve the problem of face overlapping into the first questionnaire the lessons were taught as written above.

9. Results

The first questionnaire comprised the following questions:

- A) *The principles of the projecting (1 = I did understand before this lesson; 2 = I learnt in this lesson; 3 = I still do not understand).*
- B) *The lesson was (1 = very; 2 = quite; 3 = little; 4 = not) interesting.*
- C) *I understood (1 = all; 2 = most; 3 = little; 4 = nothing) of the mathematics involved.*
- D) *I learnt (1 = a lot; 2 = quite a lot; 3 = little; 4 = not at all) new in Excel.*
- E) *I would like to continue with the Tower application (1 = yes; 2 = no).*
- F) *I am a boy (1 = yes; 2 = no).*

The number of the answers is in Table 3. The relative frequency in % is graphed in Fig. 5. The relative frequency of the answers of the boys and girls is graphed in Fig. 6 and Fig. 7. We take answers 1 and 2 in questions B–D and answer 1 in questions E–F for positive ones.

Table 3
Number of answers

	1	2	3	4
A	7	21	2	–
B	18	12	0	0
C	13	16	1	0
D	6	23	1	0
E	26	4	–	–
F	19	11	–	–

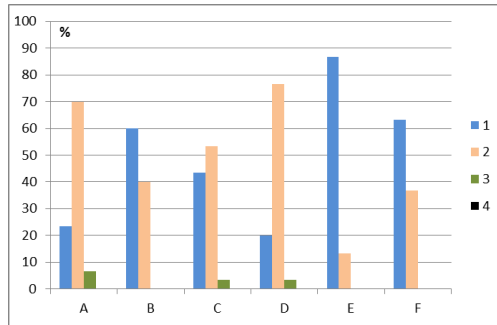


Fig. 5. Relative frequency of the answers.

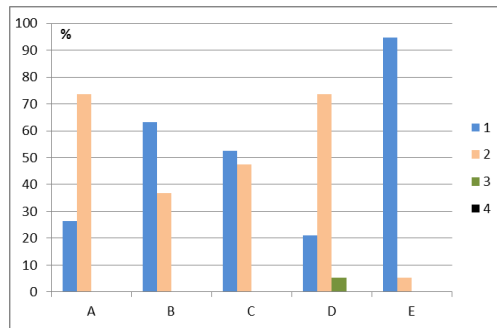


Fig. 6. Relative frequency of the answers of boys.

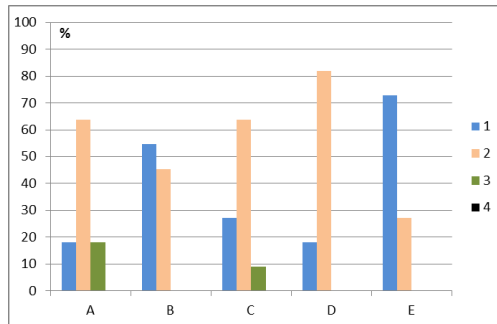


Fig. 7. Relative frequency of the answers of girls.

It holds that: (A) 23% of the students did understand the principles before the lesson, 70% learnt them in the lesson and 7% still did not understand them after the lesson, which means that 91% of those who did not understand the principles before the lesson learnt them in the lesson; (B) 100% of the students found the lesson interesting (60% very, 40% quite); (C) 43% understood everything, 53% most and 3% little of the mathematics; (D) 20% of the students learnt a lot in Excel, 77% quite a lot and 3% little; (E) 87% would have liked to continue with the Tower application; (F) 63% were boys and 37% were girls.

The number of positive answers is (question A is modified)

- A) *I did not understand the principles of the projecting before the lesson but I learnt them in the lesson: 91%.*
- B) *The lesson was interesting: 100%.*
- C) *I understood the mathematics involved: 96%.*
- D) *I learnt new in Excel: 97%.*
- E) *I would like to continue with the Tower application: 87%.*
- F) *I am a boy: 63%.*

The second questionnaire was given to the third group only. It comprised the following questions:

- A) *I would like to continue with adding colours (1 = yes; 2 = no).*
- B) *I would like to continue with more complicated figures (1 = yes; 2 = no).*
- C) *I am a boy (1 = yes; 2 = no).*

There were 8 boys and 5 girls in the group. The answer to question A was 100% “yes”. The answer to question B was 31% “yes” (4 boys) and 69% “no” (4 boys and 5 girls).

10. Conclusions

In this article, the result of an experiment was presented in which applications that depict orthographic projection of a cuboid and a tower consisting of a cuboid and pyramid with face overlapping were developed with gymnasium students of age 17–19 in two 90 minute optional informatics lessons. The participants were given two questionnaires, the first one after the lesson in which the application that depicts a cuboid was developed, the second one after the lesson in which the application that depicts a tower was developed. The aim of the survey was to find out whether the students found the lessons interesting, acquired the principles of the projection, found the lessons contributing to their technological knowledge, and found the topic motivating enough to continue with more complicated models.

The outcome of the first questionnaire is that 91% of those who did not understand the principles before the lesson learnt them in the lesson, 100% found the lessons interesting, 96% understood the mathematics involved in the topics, 87% would have liked to continue with the application that depicts a tower, and 63% were boys. The boys found the lessons more interesting than the girls and would have liked to continue with

the tower more than the girls. The result of 91% and 100% in the first and second question implies that the lesson was a success. The result of 96% and 87% in the third and fourth question implies that depicting simple 3D figures with spreadsheets has the potential to promote mathematics and informatics together at the level.

The outcome of the second questionnaire is that 100% of the students would have liked to continue with adding colours but just 31% (boys only) would have liked to continue with even more complicated figures. The result, along with 87% of positive answers to the second question in the first questionnaire, implies that depicting simple 3D figures with spreadsheets is of interest to gymnasium students. The result suggests that boys are interested in depicting even more complicated figures.

The Cuboid application is at:

https://www.dropbox.com/s/7d8hzc79kffmhcz/benacka_cuboid..xlsx?dl=0

The Tower application is at:

https://www.dropbox.com/s/8wt2p480u978ttp/benacka_tower.xlsx?dl=0

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Realistinių 3D grafikų kūrimas su „MS Excel“ – vektorinė algebra praktiškai

Jan BENACKA

Straipsnyje pristatomi rezultatai eksperimento, kuriame dalyvavo 30 gimnazijos mokinių, kurių amžius 17–19 metų. Mokiniai, naudodamiesi „MS Excel“ programa, turėjo sukurti paprastų trimačių figūrų sukamą keičiamo dydžio ortografinę projekciją. Buvo atlikta anketinė apklausa, kurios tikslas išsiaiškinti, ar mokiniai suprato projekcijos kūrimo principus. Tyrimas atskleidė, kad mokiniams patiko šios pamokos, jie įgijo daugiau technologinių žinių, tad galima ir toliau tęsti tokį pamokų ciklą su sudėtingesnėmis užduotimis.

