How to teach CAD

Andreas Asperl[1]

[1]Vienna University of Technology, aa@geometrie.tuwien.ac.at

ABSTRACT

Computer Aided Design has entered a mature stage and many areas of everyday life. Thus, CAD courses are part of many educational programs. In regard to the increasing importance of CAD education, a recent special issue of the journal Computer Aided Design was dedicated to this topic. Though the articles presented are certainly highly interesting, they contain little information on how to teach CAD in practice. The tutorial at hand tries to fill this gap.

CAD has been part of various geometry curricula at Austrian secondary schools since 1989. Working with CAD belongs to the basic skills an average Austrian pupil should be taught starting at the age of 13. Based on 15 years of experience in teaching CAD at all levels - from secondary school to graduate courses at University - this tutorial will outline the fundamental geometric and general concepts, curricula for different stages of CAD knowledge, new teaching methods and didactical principles, and the new role of the teacher. By showing typical examples of teaching sequences and results of student projects, this presentation will focus on the most important rules for `How to teach CAD'.

Keywords: teaching CAD, didactical principles, CAD curriculum.

1. INTRODUCTION

Since 1989 CAD has been part of various geometry curricula in Austria. The following table shows how wide spread CAD education is and which pupils/students get acquainted with basics of CAD:

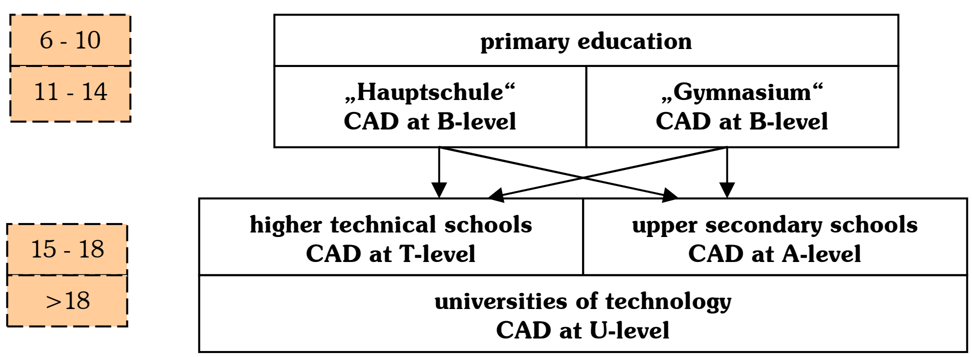

Fig. 1. Austrian school system

After 4 years of primary education Austrian pupils decide whether they attend a so called “Hauptschule” (with a lower level of secondary education) or a “Gymnasium” with significance of programs. All participants of “Hauptschul” education and about half the pupils of “Gymnasium” have lessons in “geometric drawing” in their 8th grade. Beside basic geometric knowledge and skills they should learn basic ideas of CAD. These pupils have to attend a 2-hour lesson for one year, so they get a 40-hour course in CAD all in all. About 85% of all pupils at secondary schools belong to this group. They are taught CAD at a beginners’ level (B-level). Compulsory school attendance ends after nine years of education. Then higher education splits into specific professional training at higher technical schools (HTL) and general education at upper secondary schools (AHS). These two types of education have different intentions and aims. As a result there are different demands on CAD education. Graduates of higher technical schools, who mostly get jobs in building or industrial enterprises, are taught CAD at T-level (technician level), whereas pupils attending upper

secondary schools should learn CAD at a more general level, let's call it A-level (advanced level). In 2000 I started an initiative in upper secondary school to implement education of spatial geometry using CAD instead of classical descriptive geometry lessons. The contents of theses courses have now become part of a syllabus for all upper secondary schools. The last group of CAD students, which we want to refer to, are freshmen attending lessons for architectural or civil engineering studies (U-level). At Vienna's University of Technology we started to educate these first year students with a new curriculum in 2001. There we have a heterogeneous group of students, some bring along a lot of CAD knowledge and skills and some have never even heard about CAD.
In the first part of this paper I'll show basic topics and curricula of CAD education at different levels using concrete examples elaborated by my pupils and students.
Teaching CAD at various stages of knowledge and age demands a different access and different didactical concepts, but there are some fundamental geometric and general ideas, which have to be followed. We will focus on

- some basic rules
- various models of teaching and
- suggestions for appropriate examinations

to ensure a good CAD education. It is impossible to outline all these aspects in detail, so we will focus just on most important topics.

3. CURRICULUA AND STUDENT WORKS

3.1 Secondary schools (pupils of 13 - 14 years) - CAD at B-Level

According to psychologists the best age to improve spatial ability is between 13 and 14. So it's a good idea to start 3D modeling at this early age, though at the beginning of CAD education there should be a short introduction into 2D construction techniques. Pupils at this stage of geometric knowledge have often difficulties to recognize the virtual, Euclidian concept of a point. Consequently methodologically sound software should visualize points for example as prominent squares or circles, to facilitate input and identification of points. Moreover a good beginner's software has to support snapping of elements in such a way, that the user can easily recognize that he does snap or not. Other important requirements of a beginner's software are

- meaningful icons
- manageable number of construction tools and
- a possibility to change constructions dynamically in an easy way.

Most of modern dynamic geometry software achieves these requirements and so starting with programs like Geometers Sketchpad, Cinderella, Euklid, ZUL and so on supports the students in trying their first steps with CAD. Asking interesting geometric questions [1],[3], which can be answered by using dynamic software, motivates pupils to engage more in learning CAD software.
A typical example is the following:
Example 1: "Start with a triangle ABC and construct trisections of the angles. Thus one generates three points of intersection named A', B' and C'. Which special properties belong to the triangle A'B'C'?"

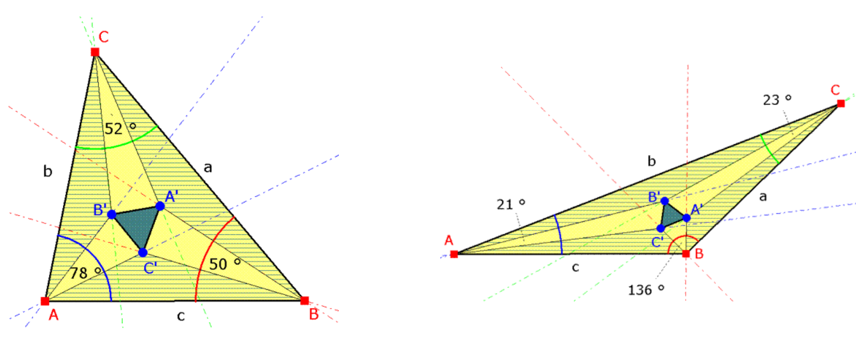

Fig. 2. Beginner's example using dynamic software

After a short phase of introduction of principles of 2D constructions it is very convenient to start immediately with 3D modeling. We strongly suggest using didactical software (easy to learn and use, but with less functionality) which allows only following actions:

- building objects with primitives (slab, sphere, cylinder, cone, pyramid and torus)
- changing the shapes of primitives by applying Boolean operations
- applying spatial transformations (translation, rotation, mirroring and scaling)
- cutting of edges

At this early stage of CAD education we mainly train the pupil's abilities

- to analyze the geometric structure of real objects
- to realize, how Boolean operations work and
- to imagine the three dimensional space (using transformations).

To promote these intentions we encourage

- to start with well-defined, self-contained tasks, which can be solved with few operations and within short time
- to work exclusively with blocks (don't use objects of extrusion, though there exist different opinions, whether the concept of bodies of extrusion should already be introduced at beginners' level)
- to provide some exercises to tighten the theoretical background (Fig. 3a) and
- to use colors to improve visualization of the geometric structure of real objects (Fig. 3b).

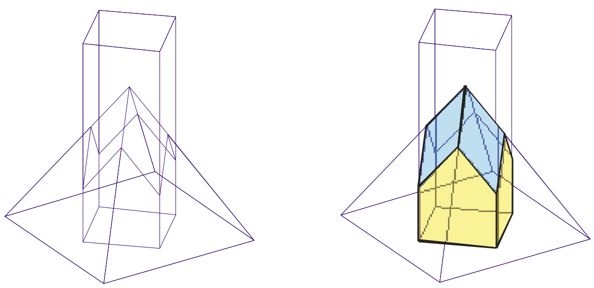
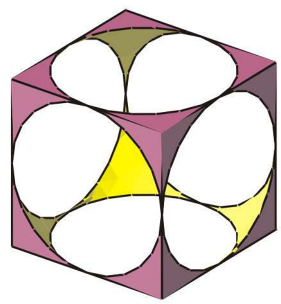

Fig. 3a. Given the wireframe representation students have to sketch the Boolean intersection.
Fig. 3b With the help of different colors students can easily recognize the Boolean difference and the involved primitives.

Example 2: Analyze the "Baumhaus" from Piet Blom and try to model a city of such extraordinary houses.

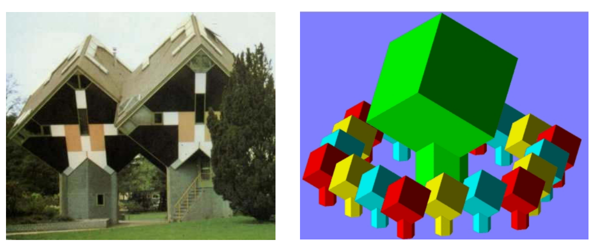

Fig. 4. Original picture and students work of P. Blom's "Baumhaus".

This example demonstrates that a CAD learner has to recognize the basic objects (a cube and a hexagonal prism), the necessary spatial transformations (rotations and translations) and the correct Boolean operation (union). To model a city of touching houses the student once more has to sharpen his spatial abilities by finding the right translations.
According to Ye et. al. [5], who tried to find out which mathematical foundation of CAD is needed, we would say that at B-level we require almost no mathematical knowledge, but we assume a lot of prerequisite geometric knowledge.

3.2 Higher technical schools (15-16 years) – CAD at T-level

In Austria young people attend higher technical schools to become tomorrow's engineers and typical CAD users in small companies. Thus CAD education focuses on teaching the essentials of everyday use of CAD. By using professional software which fits best to the demands of their future jobs, pupils should improve their basic skills (B-level), which they have learned the years before.
A curriculum at T-level must include following topics:

- generating bodies of extrusion

- excellent knowledge of feature based modeling (chamfer, blends, drills, boss, …)
- working with parameter driven objects
- recognition of different structure of surfaces and bodies
- working with and basic knowledge on Bezier curves and B-spline curves
- modeling with objects which can be generated by classical transformations (revolution, screwing, scaling, extrusion along one path, sweeps, …)
- correct use of trimming and splitting techniques
- basic knowledge of freeform surfaces
- adequate use of different coordinate systems (Cartesian, polar, auxiliary coordinate systems, …)

According to Ye et. al. [5] most of these contents are wanted by professional CAD users. Beside this, students at higher technical schools should also learn the basics of visualization, some CAD specific techniques like using and managing of layers and some basics about NURBS. Producing photo realistic pictures of real scenes is a very motivational task for CAD learners at this age and skillfully dealing with layers leads pupils to a good management and administration when working on large projects. Moreover they should know, that though Bezier curves and B-spline curves are effective tools for designing curves there are a lot of even simpler curves (circles, hyperbolae …) which demand a NURBS representation.

An extensive amount of practice time is used for *modeling* objects, but one should also try to give some exercises which require three dimensional *problem solving*. What is the difference between modeling and problem solving? This can be explained by two examples:

Example 3: Try to model a spherical casing given by the following drawing.

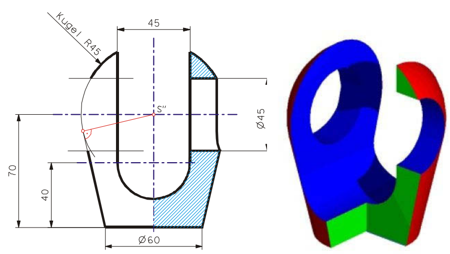

Fig. 5. Exercise and student's work of a spherical casing

Example 4: Two rollers should guide a rubber tape from position t_1 to position t_2. Given are the middle point M_1 of circle k_1, radius r_2 of circle k_2 and the positions of the two tangents t_1 and t_2. Try to find a solution.

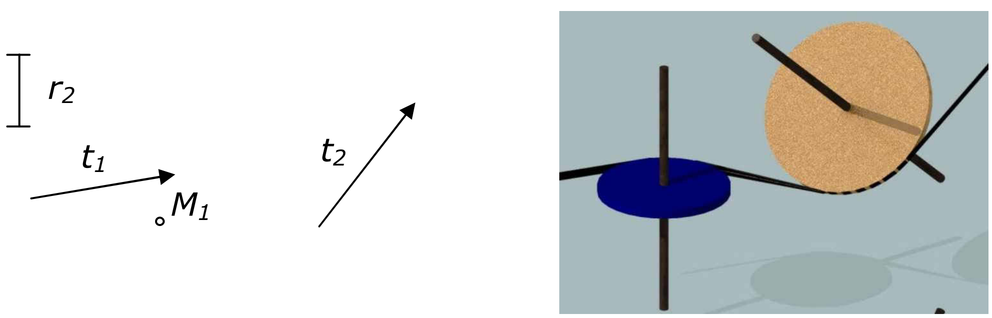

Fig. 6. Sketching of the starting position and student's solving

In example 3 the CAD learner mostly has to apply Boolean operations and spatial transformations to basic objects. To find the correct proportions of the cone he has to use some planar geometric constructions. To solve example 4 one has to make a lot of spatial considerations before starting with the concrete construction.

Example 3 promotes training of standard CAD skills while in example 4 spatial abilities are trained too. Moreover example 4 is also a good starting point for further investigations like "How does the rubber band behave? Which influence has the twisting of the rubber band on a smooth motion? …". Furthermore, instructive animations can be generated.

Because of their future job requirements pupils with CAD knowledge at *T-level* should be able to imitate real objects in their real environment. Therefore a typical and very motivating task is to analyze pictures of given objects and to model them in a freely chosen, imaginary environment.
Example 6: Lamp

Fig. 7. Original photo and student's work of a lamp

The main intention of CAD education at a technical level is to produce well trained CAD users, who work fast and effectively with every standard CAD software. They need a lot of CAD knowledge, CAD skills, computer knowledge, but only little information about the mathematical and theoretical background.

3.3 Upper secondary schools (ages 17-18 years) – CAD at A-level

The most challenging group to teach CAD consists of young people attending upper secondary schools. They learn to work with CAD and to understand the theoretical background in a more general meaning. Because teaching of descriptive geometry has a long and good tradition in Austria, we have now the possibility to introduce CAD into these lessons. Pupils at this stage of education bring in a good knowledge about basic mathematics (linear algebra, vector algebra, transforms, analytic geometry, calculus, etc.) and in most cases a lot of computer knowledge. The aim of these optional courses is to teach descriptive geometry using CAD as a new and adequate construction tool and to understand the way how CAD tools work. These CAD learners get a two-hour lesson for two years with a special exam at the end of their school career. So we have up to 120 hours for a course, in which pupils learn

- all topics of *B-* and *T-level*
- theoretical and mathematical background about Bezier- and B-spline curves
- to generate and manipulate freeform surfaces (including the mathematical theory)
- advanced techniques of visualization
- techniques of animation (working with key frames, paths and parameterized scripts) and
- to solve spatial problems.

Because of the necessity to provide a widespread and general education, the examples and tasks for these lessons come from all parts of application, technology, architecture, design, modern art, natural science, etc. The learning and understanding of the theoretical background improves the comprehension of used CAD tools. Combined with basic knowledge about the rules and properties of projections, and some elementary constructions of descriptive geometry the pupils get a very good insight into all possibilities of modern construction tools.
Using a variety of teaching/learning formats (self conducted learning sequences, working with short tutorials, team- and group works, projects …) we succeed in accelerating the learning progress. At the end of their school career pupils have to pass a four day exam. One of these examination days is now dedicated to constructing and modeling with CAD, where the pupils can show their increasing sophistication.
Some student works shall demonstrate those abilities which we want to transfer:

Fig. 8. Student's works: rollers on base of chair, kitchen knife, mini disc player

3.4 Freshmen at technical universities – CAD at U-level

The last group of CAD learners, we want to describe here, are freshmen at technical universities, who are studying architecture. From the teacher's perspective we have to cope with very heterogeneous groups; on one hand there is a declining part of students with no CAD knowledge at all and on the other hand there is a growing part of students with well developed CAD skills. Moreover some of the students bring in good mathematical background knowledge, whereas a number of freshmen have only a very basic knowledge of mathematics. But we think that spreading the idea of introducing CAD as part of general education will improve CAD qualifications of the freshmen. So we can start our academic CAD education at a common and improved level.

The students of architecture at the Vienna University for Technology attend a compulsory course (12 hours in practice and 9 hours of theory lessons) in the first term and an optional advanced course (45 hours in practice and 22 hours of theory lessons) in second term. Moreover we provide a more advanced CAD related course at the end of the studies.

In our compulsory starting course each year we have to take care of more than 500 students, which we divide into groups of about 25 participants. Each group is supervised by a graduate student. Students get a strict timetable and exact instructions. We provide small tasks, which guide students straightway through the difficulties of learning and understanding CAD in such a short time. After three 2-hour lessons and at the end of the course there are examinations.

Because of different qualifications which students bring in, we start with an easy-to-use software and teach in

- lesson 1: coordinate systems (Cartesian, spherical, cylindrical), proportions, differences between surface models and volume models, generating and placing parameter driven primitives (prism, cylinder, sphere, torus),
- lesson 2: basic transformations (translation, rotation), working with various snap modes, Boolean operations, generating simple bodies of extrusion,
- lesson 3: regular polyhedrons, auxiliary coordinate systems, rotation about an axis in general position, generating complex bodies of extrusion, scaling,
- lesson 4: basics of perspective (construction by hand and with CAD), basics of construction of shadows using distant light, user coordinate systems, global and local coordinate systems,
- lesson 5: generating and manipulating spline curves, generating area models using contour lines, using layers for structuring CAD models, generating surfaces of revolution, analyzing and reconstructing real built objects,
- lesson 6: trimming, splitting und stitching of surfaces, quadrics.

At the end of each lesson students should be able to solve for instance the following modeling tasks (Fig. 8). Notice that we don't teach any basics about visualization, so most of the student's works are in simple colors.

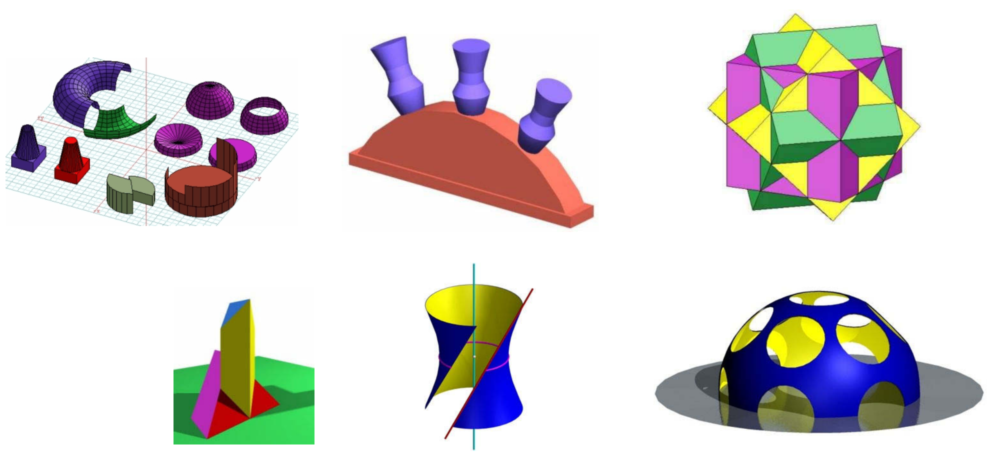

Fig. 8. Examples of the six lessons (from left to right, top to bottom)

In the second term we also provide a more advanced CAD education, where students can improve their skills by applying their knowledge to a large architectural project. There we also broaden the students' theoretical and practical knowledge on freeform surfaces.

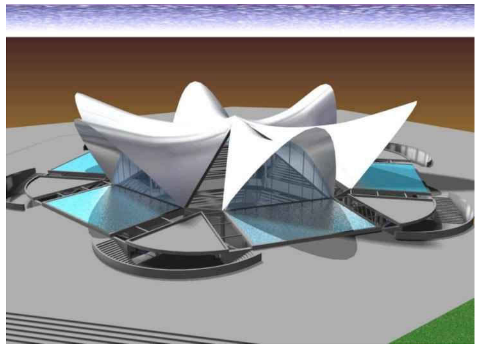

Fig. 9. Chicago airport, modelled by Kim Son Hyang and Hwang Yong Gil (2nd term), TU Vienna

At the end of their study of architecture, students can attend a course "Developing of new geometries for architects", where they get for example knowledge about practical use of a 3D laser scanner and more sophisticated techniques like reverse engineering, rapid prototyping, etc.

4. DIDACTICAL PRINCIPLES

For all of the courses presented in section 3 we try to follow some didactical principles, so that we get more students at the preferred level of skills and knowledge. One of the most important factors is the positive motivation of CAD learners. There are at least two basic motivations – to get good marks in examinations and to be well prepared for further tasks. But one should try to improve these motivations by other arrangements, because motivation is the most powerful motive for learning not only new things. By interviewing pupils/students of all ages we can state following suggestions as most important ones:

- Let students choose the degree of difficulty of their tasks in each sequence by themselves!
  We provide a lot of different, but approximately similar exercises. Thus students are motivated, because they have the opportunity to choose exercises according to their individual level of skills. This helps us to avoid students, who are over or under taxed. If we expect too much from our students, they leave our lessons frustrated without acquiring the necessary abilities. On the other hand, if we expect too little, the lessons are boring for better students.
- Present your students mini tutorials!
  One- or two-sided manuals with instructions and screenshots should guide the CAD learner through the difficulties of the process of modeling and constructing an object. Thus students can control the speed of their personal learning progress, and education time is saved. Some software companies even provide short movies to introduce handling of special software tools.
- Provide realistic objects and examples, which suit the age and the future profession of students!
  If our students believe strongly, that they can use their CAD knowledge in every day life they will learn with more motivation.
  Pupils at the age of 13 to 14 will learn the basics of modeling by using objects from a real construction set, so in a first step they can build their objects in the real world. Regularly it's easier for people with less spatial ability to touch the objects in real space in order to understand the underlying geometric structure. In German the word "begreifen" means both: touch an object and understand something!
  Older CAD learners prefer modeling of objects at a more technical level or they tend to look for interesting objects coming from modern design and art. The more mental channels are affected, the better the output will be.
- Offer real and virtual models!
  As we stated before, touching real objects leads to a better insight, but it's often difficult or impossible to provide enough real objects for a large group of students. A very good compromise between real objects and sketched representation is the use of VRML models. These models can be turned around and nearly give the impression of dealing with real objects.
  Using colors to mark special features like blending, chamfers, etc. relieves even more the recognition of the underlying geometric structures.

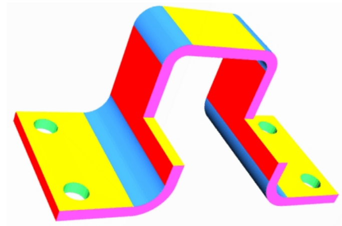

Fig. 10. The use of color and VRML supports recognition of the geometrical structure of objects.

- Enliven your lessons with small and large projects!
  Already at the beginning of our CAD courses we promote self-paced learning and creativity of our students by demanding the realization of smaller projects. Topic and deadline are given by the teacher, but execution and timetable are the student's responsibility. After finishing the project the students should present their work to their classmates. In most cases this is an extra incentive for a little competition which increases motivation enormously. In addition the students learn to cope with time management and presentation.
- Incorporate partner- and teamwork with your CAD courses!
  If students work together they are learning faster by mutual help. Students often explain construction processes in their own, specific language, which is sometimes easier to be understood by their colleagues than the technical lecture of an instructor. Students who are forced to explain their individual way of construction get a better insight in their personal doing. Telling somebody what to do is sometimes much harder than just doing it.
  Additionally students improve social competence and their ability to work in groups. Moreover they experience problems with data exchange and learn to deal with them. In combination with larger projects partner- and teamwork leads to interesting outcomes, which are motivating all participants–CAD learners and their instructors.

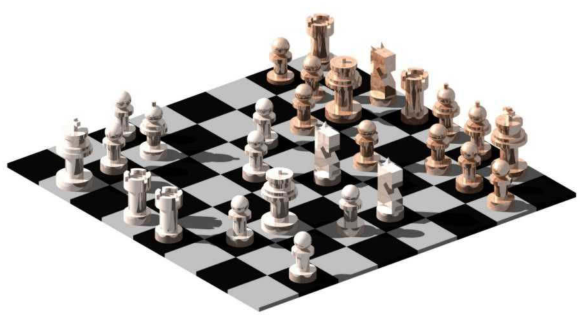

Fig. 11. Small project: chess

Wittmann states in [4] that good lessons should provide a variety of teaching and learning formats to elevate many students to a high level of skills and knowledge. The more colorful lessons are, the more mental channels of CAD learners will be affected and the better the output will be.

5. TEACHER'S ROLE AND SKILLS

As a consequence of this the position and role of teachers has to change, too. Teaching in front of the audience and explaining constructions step by step should be only a small part of successful CAD education as well as in other subjects. The teacher should not be the center of activities; it is more efficient to put the individual student into the center. In comparison with team sports, a good CAD teacher has not to be the "most valuable" CAD player, but he has to be the best coach.

Notice that there is a big difference between *modeling and solving problems with CAD* and teaching or encouraging someone to do so!

5.1 Some principles for practicing good education in CAD

To meet qualifications for this new position there are some simple considerations which should be obeyed when teaching CAD.

A good CAD teacher should understand the difficulties of learning CAD and he/she should be able to counteract with these problems in various ways.
Often instructors of CAD courses, coming from various areas of practice, have a lot of practical skills and theoretical knowledge, but they sometimes don't realize or even know the difficulties CAD learners have to deal with. Students and teachers often are of different age, social background and available general knowledge. Thus both parties often have different access to problem solving and working processes. If a teacher is aware of this, he/she can much easier try to adopt his/her CAD instructions to the needs of the CAD learners.
How diverse various groups of CAD learners handle a task is illustrated by the following example.
Example 4: Try to model a top of a pencil with only three operations.

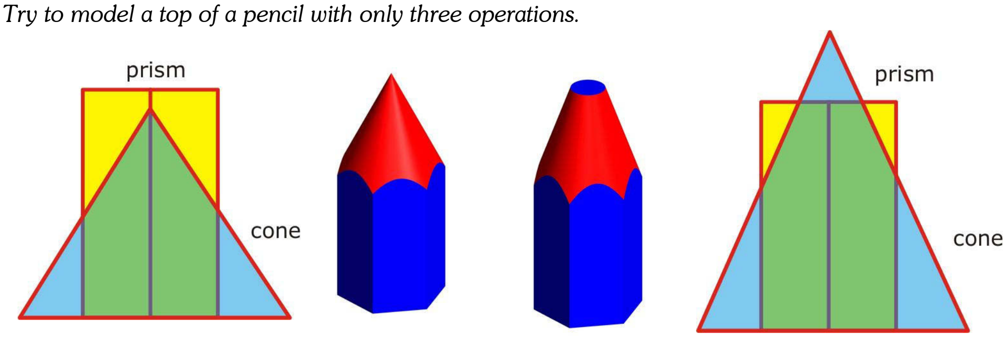

Fig. 12. Example 4 and typical fault

People educated in a classical mathematical or scientific way start with *thinking* about the problem. Pupils with less scientific educational background tend to start with *trying* various possibilities. In most cases, people with classical mathematical background start to put their mental considerations into action after about five minutes and often they fail. But then, only by looking at their false attempt, they get the "heureka"-effect and realize how to finish their object. Though both groups after all get the understanding mainly by trying, it would not be a good idea to force people with scientific educational background to begin with trials immediately.

A good CAD teacher will notice the complications of the learning process of his students.
Lessons with large parts of self determined student work give the teacher a good opportunity to monitor the learning process of his students. Thus he will find out difficulties in the learning progress at a very early stage and can deal with these troubles by providing more exercise material, personal coaching or individual teaching support.

A good CAD teacher promotes autonomous learning by problem- and process oriented sequences.
The main task of competent CAD teaching is to provide a continuous training course with a wide diversity of problems and tasks. The teacher's selection of examples steers the progress of learning, whereas the student is responsible for his personal time management. Permanent observation of the learning progress, evaluation of projects and examinations secure that most participants maximize their individual potential.

A good CAD teacher is convinced that CAD is an important part of education.
A CAD instructor who brings in a lot of enthusiasm, transfers this attitude to his students. They are encouraged by the spirit of their teacher and invest more time and power in their personal CAD education.

Summarizing we state the following desired qualifications for CAD teachers:

- good knowledge of CAD, geometry and mathematics
- educational and didactical knowledge (understanding of learning processes) and
- enthusiasm (this leads to fascination, motivation and interest of the students)

5.2 How to prepare examinations

An essential part of every education is the examination of a pupil's skills and knowledge. Hummenberger and Reichel investigate in [2] the examination behaviour in mathematic lessons and they state: "What you test is what you get?" This is also true for CAD! For that reason it is a good suggestion to think about appropriate examination tasks.
In our courses we evaluate *basic skills* with concrete, small examples. The student should be able to finish each of these tasks within a very short time by using only few operations. Thus we those abilities and skills we want to prove can be tested exactly. Rating of these examples happens on the spot.
On the other side we check *complex, advanced skills* by preparing "free problems", which allow the student/pupil to show all his/her abilities. These problems must have a variety of possible solutions. For example we provide a set of pictures showing an object or we present a short description of required features an object should have. Rating of the solution of those free problems is made together with the student. By talking about the way of construction one can assess skills and creativity of the student's work. Moreover accuracy and observation of technical conventions influence the final mark.
When testing *theoretical knowledge* of students, we have to mind that the way we ask questions determines the answer we get. For example, if we ask "What are Boolean operations?" then almost certainly we will get an answer which consists of the definition of Boolean operations. On the other hand by asking "Why do we need Boolean operations", we give the student the opportunity to show that he really understands meaning and use of Boolean operations.

6. CONCLUSIONS

Teaching CAD is a very complex topic. The range of requirements reaches from enhancing students' spatial and 3D visualization abilities up to teaching them 'how to design objects', which is a rather tricky by itself. Depending on the level and age of CAD learners there are different curricula, which direct the students to the preferred level of CAD knowledge. The higher the required education level, the more important are good geometric and mathematic knowledge.
One important topic we didn't deal with is the choice of the fitting software. Often CAD education suffers from limitations coming from CAD-software (tools don't work the way they should, the user interface is not appropriate, the software is not affordable for students, …).
We have listed some didactical principles and suggestions to improve CAD education at all levels, but there still exist a lot of yet unknown interactions between teacher, student and CAD software, which have to be investigated. Knowing exactly how the knowledge transfer is happening and what type of teaching support fits best, will surely lead to a further improvement of CAD education.
In this article we referred to the Austrian situation. So far all teaching material has been developed for use in Austrian schools and universities, and therefore it is available only in German (www.geometrie.tuwien.ac.at/asperl/...). However, we are most interested in an exchange of ideas and experiences, and further development of teaching material on an international level.

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