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Today's students, tomorrow's engineers: an industrial perspective on CAD education

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Abstract

Today, they are students in colleges and universities. Tomorrow, they will be engineers in various industrial sectors. One of the primary goals of education is to prepare people for successful careers in the real world. As in every course, students want to obtain the maximum value of a CAD related course for their future careers. They want to obtain knowledge and skills that are most practical and useful to them when they become engineers. College professors and teachers also want to provide the maximum value for students in their CAD courses. The question is: what should be included in such a CAD curriculum. This paper tries to answer some critical questions related to developing such a curriculum, from an industrial perspective, based on the authors' survey results and the first author's own (rather limited) experiences as a R&D staff for a CAD vendor. It focuses on issues related to teaching and training students on CAD systems. These include, for different roles, how much underlying mathematical foundations in CAD systems should be taught, how much computer skills and engineering knowledge the students should know, how much design methodologies related to CAD systems should be taught, and how much ability the students should develop in order to specify their CAD needs and to evaluate and choose the CAD systems most suitable for their specific applications. The paper then shares some personal experiences and suggestions from long-term CAD veterans on the essential topics of CAD education. Based on the survey results, last section concludes the paper by authors' suggestions on what should be included in CAD curriculums for different levels of students.

Keywords: Computer aided design; CAD education/training; CAD system development; CAD system evaluation; CAD methodology; CAD mathematical elements

1. Introduction

Today, they are students in all kind of colleges and universities, taking degree courses or career training programs. Tomorrow, they will be engineers in various industries (e.g. aerospace industries, automobile industries, consumer product industries), taking different roles in their future careers. To get some basic ideas on CAD career developments, let's listen to two typical CAD veterans:

I began my career in the CAD world with 2D drafting. I used to generate 2D drawings and 3D wire-frame models in AutoCAD R10. Continuing the same, I also started to program in AutoCAD using AutoLisp, DCL, VBA, and Visual Basic. Using these tools, I developed lot of automation programs for generating drawings, incorporating business knowledge (databases). Then I progressed to 3D modeling in Pro/E and Inventor. I then learned to customize this software using Pro/Toolkit, Visual Basic, ActiveX automation using VC++. I then progressed further to actual 3D software development of SolidWorks using VC++.

I have worked as a CAD Application Engineer in aerospace design and equipment development environments as well as for a CAD software reseller. I have worked mostly in 3D for the 18 years I have been out of college. I have worked for software development companies since 1993. My 3D experiences have been

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in wire-frame, surfacing, solid modeling, and parametric feature-based modeling. I have also worked with PDM and PLM for the past six years, mostly as it relates to CAD users

Since the beginning of CAD in the 1960s, CAD technologies have found their way into colleges and universities. Currently, in the colleges and universities, CAD technologies have been taught in different disciplines with different focuses. Some colleges and universities offer stand-alone CAD courses. These courses may focus on the whole picture of CAD, or special aspects of CAD (e.g. geometric modeling), while others focus on the use of some particular CAD systems or application development. Other universities and colleges, on the other hand, introduce some aspects of CAD technologies in courses such as Computer Graphics or Engineering Design. [5,6,11–14,21,33,34]

In Engineering disciplines such as aerospace, automobile, ship building and consumer product design disciplines, CAD technologies may be taught as tools to assist their design drawing and drafting; or as part of engineering mathematics or graphics. In Mathematics departments, CAD may be taught in forms of geometric modeling, particularly in Computer Aided Geometric Design (CAGD) or numerical processing for geometric data. In Computer Science departments, CAD may be taught as part of the Computer Graphics courses.

Regardless of where they learn, as in every course, students want to obtain the maximum value of a CAD related course for their future career: they want to obtain knowledge and skills that are most practical and useful to them when they become engineers. College professors and teachers also want to provide their students with maximum value in their CAD related courses. The question is: what should be included in such a CAD curriculum?

This paper tries to answer some critical questions related to develop such a CAD curriculum, from an industrial perspective, based on the authors' survey results and first author's own (rather limited) experiences as a R&D staff for a CAD vendor. It does not try to answer every aspect of such a curriculum. Rather, it focuses on questions related to teaching and training CAD systems.

This paper begins with a brief introduction of CAD systems and the CAD industry in Section 2. It goes on to address possible roles 'tomorrow's engineers' may take in their jobs, and what they may need to know for their jobs from a larger perspective. These include:

- mathematical foundations of CAD systems in Section 3;
- computer science and engineering aspects of CAD systems and related developments in Section 4;
- design methodologies related to CAD systems in Section 5;
- the ability to specify their particular CAD requirements, and to evaluate and choose commercial CAD systems most suitable for their specific applications in Section 6;
- and knowledge and skills on other related fields in Section 7.

Based on the survey results, Section 8 concludes the paper with authors' suggestions on what should be included in CAD curriculums for students in undergraduate, graduate and advanced levels.

2. CAD systems and CAD people

CAD cannot exist without commercial CAD systems that have been developed to automate the design processes. Industrial applications are the driving forces for the development of CAD technologies and CAD systems. Early development of CAD systems had been backed by major manufacturing companies. During the past three decades, CAD systems have evolved from Computer Assisted Drawing/Drafting, to Computer Aided Design, and to a stage now called by most CAD software vendors: Product Lifecycle Management [8,9,15,18]. The modeling technologies, on their own, have evolved from wire-frame modeling, to surface modeling [1,2,3,7,19,20, 23,38], to solid modeling [22,25], and to feature-based parametric modeling [26,35,36]. The computer platform has evolved from proprietary computer systems, to UNIX-based mainframes and workstations, and to Windows-based PCs. The CAD professional training activities started from day one of the commercial CAD systems, progressing from 2D drawing systems to 3D modeling systems.

With the development of CAD technologies and the gradual adoption of CAD systems by industry, the responsibilities of developing, maintaining, and supporting CAD systems have transferred from manufacturing companies to software companies, through spin-off, merging, and reorganization. Regardless of how the CAD industry evolves, students in colleges and universities want to learn technologies that can best serve their future careers. The criteria, however, will vary from person to person, from professional to professional, and from job to job. Therefore, in order to understand what CAD knowledge and skills can best serve the students, we need to first understand the CAD related roles they may play in their future careers. Below is a list of possible roles.

- *CAD user*. A person who uses CAD tools in his/her job. A CAD user is a customer of CAD software vendor(s), also a called CAD operator. He/she is normally a draft person or a design engineer.
- *CAD application developer*. A person who develops CAD software packages for specific applications based on the Application Programming Interfaces (APIs) that are provided by the software vendors. The application software he/she develops can be specific to him/her, or

can be part of a commercially available software package for special engineering fields. In the latter case, he/she is a software developer for that software package, and is normally called a third party developer.
- *CAD software developer*. A person who develops CAD software system as an R&D staff member. This category also increasingly includes third party developers who have direct access to source codes of the CAD software system.
- *CAD manager*. A CAD manager is a person who manages CAD related activities for his company. There are at least three types of CAD managers: (a) those who manage CAD users; (b) those who manage CAD software developers; (c) those who manage CAD application developers or third party developers. In this paper, we restrict the meaning of CAD manager to include only the first category.
- *Others*. This category includes all other people involved in CAD related activities, e.g. supporting staff, marketing and sales personnel. This category is not the focus of this paper.

Most people take different roles in different time periods during their CAD careers. For example, the first CAD veteran mentioned in Section 1 started as a *CAD user*. Then he became a *CAD application developer* based on a 2D CAD system, and then a *CAD application developer* on 3D CAD systems. Now, he is a *CAD software developer* based on a 3D CAD system. Even during a specific time period, a person may take different roles, e.g. he may be a *CAD manager*, and, at the same time, a *CAD application developer*, and a salesman for his own CAD related products.

Our focuses in this paper are categories (1)–(4). To find out what can best serve the students for their future careers, we designed a questionnaire for the above four categories of people, with the categories of questions for survey listed in Section 1. We conducted a survey with the questionnaire in leading CAD companies in the world, mostly from the USA, with a fairly large percentage from SolidWorks Corporation. About 150 answers have been returned (a person who answered the questionnaires from different role perspectives will be counted as multiple answers). Most of the people participated in the survey are long-term CAD veterans: in average 10 + years' CAD experience, and a large percentage of them have 15 + years' CAD experience, some even have 30 + years' CAD experience. They are from different departments (research and development, third party application development, quality assurance and support, marketing, sales, etc.). Most of them have taken different roles in their CAD careers. Based on the survey results and the first author's experiences (as a R&D staff in SolidWorks Corporation), in the rest of the paper, we will discuss these questions one by one in the following sections.

3. Mathematical foundation of CAD

Currently, the mathematical elements being taught in CAD related courses in colleges and universities can be classified into the following categories:

- *Basic mathematics*. Linear algebra, vector algebra, transforms, basic analytic geometry [10], equations (algebra, ordinary differential equations, partial differential equations), calculus, etc.
- *Advanced mathematics*. Analytic curves and surfaces, basic differential geometries [17], basic optimization techniques.
- Advanced CAD topics: [2,3,7,19,20,22,23,25,28,31, 32,37,38]
  - (a) Non-Uniform Rational B-Spline (NURBS) curves and surfaces;
  - (b) Boundary representations (B-reps) and Constructive Solid Geometry (CSG) techniques;
  - (c) Intersections (curve/curve, curve/surface, surface/surface) and Boolean operations.
- Other advanced CAD topics, such as:
  - (a) Non-linear equation solvers;
  - (b) Constraint solvers; [35]
  - (c) Shape interrogations (e.g. curvature maps, contouring, offsets, geodesics, zebra strips, and reflection lines). [27]

In our view, all CAD people whose roles are listed in Section 2, including marketing and sales personnel, should know the basic mathematical elements well. These elements are taught in undergraduate mathematics courses. Courses for basic differential geometries and basic optimization techniques are offered in undergraduate or graduate courses in Mathematics or Engineering disciplines. Topics listed in Item 4 form the underlying mathematical foundations of those topics in Item 3. For example, a constraint solver is the basis of sketching and hence the foundation of parametric design; a non-linear equation solver is the basis for intersections and therefore the foundation of Boolean operations. Granted, these should be understood by people who develop the corresponding specific software (e.g. constraint solver software, intersectors, etc.), and are not be crucial for other CAD people to understand.

On the other hand, topics listed in Item 3, namely NURBS, B-rep/CSG and Intersection/Boolean, are the fundamental elements of CAD systems. They are closer to CAD users than those topics in Item 4, and should be understood by a wider spectrum of CAD people. It is based on the above grounds that we designed Table 1 as the questions in our survey questionnaire.

Throughout the paper, Level 'A' means nothing should be known for this topic. Level 'C' means in-depth knowledge should be learnt for this topic. Level 'B' is between Levels A and C, in general, it means fundamentals

Table 1
Survey on mathematical foundations for CAD

Math. Foundation	CAD roles			
	CAD user	CAD application developer	CAD software developer	CAD manager
Analytic curve and surface	[27] A	[5] A	[2] A	[22] A
	[70] B	[56] B	[9] B	[72] B
	[3] C	[39] C	[89] C	[6] C
NURBS curve and surface	[58] A	[11] A	[5] A	[40] A
	[39] B	[61] B	[21] B	[54] B
	[3] C	[28] C	[74] C	[6] C
Intersection and Boolean operation	[24] A	[2] A	[2] A	[22] A
	[68] B	[56] B	[14] B	[69] B
	[8] C	[42] C	[84] C	[9] C
B-reps and CSG	[68] A	[3] A	[2] A	[31] A
	[30] B	[58] B	[21] B	[56] B
	[2] C	[39] C	[77] C	[13] C

should be known for this topic, although it is hard to define what that is. For each topic and role, only ONE item of A, B and C should be checked. The number listed in each square bracket in the tables is the percentage number voted for that item.

Table 1 contains the survey results of the mathematical topics. The survey results show that CAD users should know the fundamentals of Analytic Curves and Surfaces (70%) and Intersections/Booleans (68%), although not in great depth. On the other hand, they do not need to know anything about NURBS (58%) or B-Reps/CSG (68%). These results do not come as surprise considering that CAD users often use analytic geometries in sketching and part building; and that trimming is often used in building complex parts. They would like very much to leave the NURBS and B-Reps/CSG to the CAD system developers, and rely on CAD systems to deal with NURBS and B-Reps/CSG for them.

The survey reveals that CAD software developers and CAD application developer need to know all the four topics listed in Table 1, but to different extents. CAD software developers need to know all the math topics in-depth; and CAD application developers need to know these topics to a lesser extent. Granted, not every CAD software developer needs to know topics such as NURBS, e.g. UI developers. However, the survey quantifies the extent of knowledge required. CAD managers, on the other hand, need to know only the fundamentals of these topics. These survey results are rather reasonable and expected.

In addition to the mathematical elements mentioned in this section, Manufacturing Processes such as CAM, Mold, stamping process, sheet metal process are also mentioned by one return sheet as fundamentals that should be understood by CAD people mathematically.

4. Computer knowledge and skills for CAD

CAD cannot exist without computers: after all, it is a computer tool that engineers use to help in their designs. Engineers design their models in the computer as a mock-up of the real-world physical models. In order to be able to develop or use CAD tools efficiently, engineers need to have knowledge and skills in computer science and engineering.

The knowledge and skills that are most pertinent to engineers are programming languages, knowledge related to programming techniques and architectures, and Internet technologies. Programming languages include C, C++, vendor provided APIs such as AutoLisp for AutoCAD, and VBA for API programming. Programming techniques and architectures and design include data structure and database technologies. Data structure in this paper is a general Computer Science concept, not the concept of product model data structure used in the design and manufacturing communities. The Internet is becoming an indispensable part of our work and life, and so it is for engineers in their design. For example, engineers need to distribute their designs remotely for review and markup by their colleagues or managers.

To find out how much computer knowledge and skills should be taught for CAD purpose in colleges and universities, Table 2 is used in the survey. The survey shows that all CAD people should have some knowledge of computer hardware (65%). However, they do not all need to be hardware experts, except for CAD software developers, who are required to be very good at hardware. For vendor-provided APIs and VBA programming, CAD users may not need to know much (51%), but it might be helpful if they choose to learn the fundamentals (43%). CAD managers should know these tools to some extent, while CAD software developers and CAD application developers must have in-depth knowledge of them.

Similar results can be found for C/C++ programming languages and data structures. The survey reveals that CAD users should not be required to have any programming related skills and knowledge (C/C++: 86%, data structure: 89%), while CAD managers are required to know the fundamentals. CAD application developers and CAD software developers should have in-depth programming knowledge and skills, especially CAD software developers who absolutely should have a very deep understanding of them.

The survey also shows that everybody needs to know the fundamentals of database and Internet technologies. CAD software developers are required to have in-depth knowledge of these technologies (about 50%). CAD application developers should also have knowledge of these technologies, but to a lesser extent (about 39%). CAD managers, on the other hand, are only required to know the basics of these technologies.

Table 2
Survey on computer science aspects of CAD

Computer science and programming knowledge	CAD roles			
	CAD user	CAD application developer	CAD software developer	CAD manager
Computer hardware	[32] A	[8] A	[5] A	[8] A
	[65] B	[64] B	[60] B	[78] B
	[3] C	[28] C	[35] C	[14] C
Vendor-provided APIs	[51] A	[3] A	[7] A	[22] A
	[43] B	[25] B	[28] B	[72] B
	[6] C	[72] C	[65] C	[6] C
VBA	[65] A	[0] A	[5] A	[28] A
	[30] B	[42] B	[51] B	[64] B
	[5] C	[58] C	[44] C	[8] C
C/C++	[86] A	[5] A	[5] A	[33] A
	[8] B	[26] B	[5] B	[44] B
	[6] C	[69] C	[90] C	[23] C
Data structure	[89] A	[14] A	[2] A	[26] A
	[9] B	[29] B	[5] B	[51] B
	[2] C	[57] C	[93] C	[23] C
Database technology	[51] A	[6] A	[20] A	[14] A
	[46] B	[56] B	[29] B	[68] B
	[3] C	[38] C	[51] C	[18] C
Internet technology	[35] A	[3] A	[14] A	[11] A
	[57] B	[58] B	[37] B	[78] B
	[8] C	[39] C	[49] C	[11] C

5. CAD design methodologies

CAD system developers have been trying very hard to incorporate ways/methodologies engineers are using in their design, in order to better help engineers with their design process. Design methodologies here refer to design philosophy, design methods and their realization in CAD systems. More specifically: [4,8,9,16,24,29,30,35]

- *Design philosophy*. Such as top–down/bottom–up design;
- *Parametric modeling*: A way to create product models parametrically. The center piece of parametric modeling is a constraint solver, and sketching is based on the solver;
- *Feature-based modeling*. A way to create product models by means of features, including part modeling, assembly and drawing. Usually design history is recorded as a history tree;
- *Concurrent engineering*. Refers to integration of the product design, development and manufacturing processes in order to decrease the product lead time;
- *Network-centric collaborative design*. With the rapid development of network technologies, design data can be collaborated for the purpose of, e.g. design review;
- *Creative design*. This category includes knowledge-based design (incorporating design knowledge in CAD systems), design reuse (in connection with part library, is a way to design new CAD models based on existing CAD models, reusing parts or whole of the old models).

Notice that the above items can overlap each other. For example, feature based design and parametric design are the mainstream technologies in CAD systems. They are strongly overlapping. Nevertheless, they are different technologies on their own, and are listed separately in the survey. In addition, this section also tries to find out the necessity of understanding the following important design related fields since design and manufacturing automation have been evolved to a stage that they no longer only help the designers individually, but also team-wise and enterprise-wise; not only in the design process, but also during the whole life cycle of the products.

- *Reverse engineering*. Refers to the process of creating a digital model in CAD systems from an existing physical model. New design will be based on the digital model;
- *Part family design*. Also called model configuration or model series, refer to the models that only differ in dimensions to a mother model;
- *PDM/PLM*. PDM refers to Product Data Management, PLM refers to Product Lifecycle Management;
- *ERP*. ERP refers to Enterprise Resource Planning.

Tables 3 and 4 are used in the survey for CAD design methodologies and the CAD related fields, respectively. The survey reveals that all CAD people are required to have in-depth knowledge on top–down/bottom–up design methodology, parametric modeling technology, feature-based modeling technology and part family design. CAD users and CAD managers in particular should be very good at the top–down/bottom–up design methodology (60%), while CAD application developers and CAD software developers need to know it in-depth but to a lesser extent (46%). CAD software developers should have very deep knowledge of parametric design technology (75%), while people in other categories should know this technology in-depth but to a lesser extent (41–49%). CAD users and CAD software developers need to know feature based modeling technology very well (66–68%), while CAD managers to a lesser degree (51%), and CAD application developer to an even lesser degree (43%). Similar results are found in the survey for part family design.

The survey also reveals that all CAD people are required to know the fundamentals of reverse engineering technology, concurrent design technology, and network centric collaborative design technology, although only CAD

Table 3
Survey on CAD design methodologies

CAD methodology (+ related knowledge)	CAD roles			
	CAD user	CAD application developer	CAD software developer	CAD manager
Top–down/bottom–up design	[11] A	[11] A	[10] A	[9] A
	[29] B	[43] B	[45] B	[32] B
	[61] C	[46] C	[45] C	[59] C
Parametric modeling	[14] A	[8] A	[5] A	[2] A
	[39] B	[51] B	[20] B	[49] B
	[47] C	[41] C	[75] C	[49] C
Feature-based modeling	[5] A	[6] A	[5] A	[3] A
	[29] B	[51] B	[27] B	[46] B
	[66] C	[43] C	[68] C	[51] C
Concurrent engineering	[11] A	[9] A	[9] A	[5] A
	[50] B	[68] B	[59] B	[49] B
	[39] C	[23] C	[32] C	[46] C
Network centric collaborative design	[18] A	[8] A	[13] A	[8] A
	[58] B	[68] B	[55] B	[54] B
	[24] C	[24] C	[32] C	[38] C
Creative design (knowledge/p art library)	[13] A	[13] A	[16] A	[8] A
	[55] B	[55] B	[52] B	[51] B
	[32] C	[32] C	[32] C	[41] C

managers are required to have some in-depth knowledge about them. To a lesser extent, all CAD people are required to know the fundamentals on PDM, PLM and ERP, but it is the CAD manager's job to know them in-depth.

Table 4
Survey on CAD related fields

CAD methodology (+ related knowledge)	CAD roles			
	CAD user	CAD application developer	CAD software developer	CAD manager
Reverse engineering	[26] A	[17] A	[14] A	[14] A
	[50] B	[59] B	[66] B	[56] B
	[24] C	[24] C	[20] C	[30] C
Part family design	[2] A	[6] A	[9] A	[6] A
	[37] B	[51] B	[30] B	[51] B
	[61] C	[43] C	[61] C	[43] C
PDM/PLM	[10] A	[16] A	[17] A	[11] A
	[74] B	[55] B	[53] B	[35] B
	[16] C	[29] C	[30] C	[54] C
ERP	[44] A	[36] A	[33] A	[16] A
	[56] B	[52] B	[65] B	[48] B
	[0] C	[12] C	[2] C	[36] C

6. CAD system evaluations

CAD system evaluation is an important part of CAD application. Before even becoming a CAD user, a potential user might be involved in a system evaluation process that can lead to a purchase deal. Although CAD system evaluation is usually part of a larger engineering system evaluation, which may in addition involve company specific procedures, policies, and different departments, there are some aspects that are common to the CAD system evaluations.

Each commercial CAD system has its strong points and weak points. Before investing on a CAD system, one needs to know the following aspects of the system in comparison with other similar CAD systems:

- The application domains of the system: does it match your industrial sector(s) and your specific applications?
- What are the strengths of the system? Are they important for your specific applications?
- What kinds of training are needed in order to use the system? How easy is it to learn and to use?
- What are the software and hardware environments for the CAD system? What is the cost?
- Does the vendor provide good services to its customers? A deal on a CAD system includes not only a good value for the money, but also a good relationship with the vendor.
- How well does the system support API-based application development?
- How well does the system support reuse of your existing designs, in terms of, e.g. data exchange and reverse engineering?

CAD users need to evaluate candidate systems before proposing a deal to their managers, who will make the final decisions on choosing a particular CAD system(s) for their specific applications. CAD application developers need to find a CAD system on which their applications can be built. Even CAD software developers need to know the strong and weak points of CAD systems in order to know what's missing in their own system(s). It is safe to say that all CAD people need to know how to evaluate CAD systems. The question is, to what degree do they need the knowledge and skills of CAD system evaluations? To find out the answer, we designed Table 5 and used it in our survey.

The survey clearly shows that it is the CAD manager's job to know in-depth how to evaluate CAD systems (68%). People in other categories are required to know the fundamentals of the criteria: on average 53% in establishing the evaluation criteria; 52% for establishing the evaluation benchmarks; 60% for application domains).

Table 5
Survey on CAD system evaluations

CAD system evaluation knowledge	CAD roles			
	CAD user	CAD application developer	CAD software developer	CAD manager
Establishing the evaluation criteria	[11] A	[17] A	[29] A	[8] A
	[57] B	[51] B	[50] B	[22] B
	[32] C	[32] C	[21] C	[70] C
Establishing the evaluation benchmarks	[16] A	[16] A	[34] A	[8] A
	[55] B	[54] B	[48] B	[24] B
	[29] C	[30] C	[18] C	[68] C
Merits/shorts of different CAD systems	[10] A	[14] A	[9] A	[8] A
	[61] B	[54] B	[68] B	[24] B
	[29] C	[32] C	[23] C	[68] C
Application domains/ industrial sectors	[16] A	[8] A	[11] A	[8] A
	[66] B	[46] B	[66] B	[30] B
	[18] C	[46] C	[23] C	[62] C

7. Improving CAD education

In the survey, the participants were asked what they think about the current status of CAD education in colleges and universities. Only 8% of the participants think that current CAD education is adequate. 18% of the participants think that they have been taught too much, either in mathematics, or in computer science, or in mechanical engineering. 74% of the participants think they should have been taught more, in the order of, practical training, application development, computer science, mathematics, and mechanical engineering. This survey does not specify what specific subjects in the above-mentioned disciplines, e.g. whether NURBS in Mathematics, should be taught more. Below are comments made by two participants:

> In general, current CAD education and training in colleges are far from adequate. Some colleges are still just teaching students simple 2D drawing skills (like AutoCAD). Even though some colleges have switched to 3D packages, the syllabus they present to students is not comprehensive and systematic. It is somewhat hard for students to get a big and clear picture of the CAD technology

> Many programs focus more on mechanical engineering and CAD usage within that respect, rather than CAD development/theory. Very few programs focus on CAD theory, except in research labs. Granted, it is an obscure field to study, but…While in graduate school I taught the CAD class for undergraduate students (most sophomores and juniors). The curriculum given to me by the faculty focused entirely on CAD tools and skills (how to draw a line…), rather than the application of CAD to Engineering, or the theory of CAD. Students came out of the class with knowledge of what buttons to push, but not how to use the CAD software to enhance the design process, and with very little knowledge of how CAD works. As with anything, knowing how something works can help you use it more effectively.

Many survey participants also provided suggestions on how to view CAD and improve CAD education. Let's listen to what they say.

7.1. No formal requirements but courses for CAD

> I myself will strongly disagree with setting up a formal requirement for CAD because of the reasons below. A good general mathematical, engineering, computer science, or scientific education would be sufficient. The CAD courses should be available, however.CAD is just a trade that people can learn fairly easily once they have been exposed to it for a few months. The foremost requirement is that people will use their knowledge of mathematics, engineering, computers, and their imagination in the CAD environment.CAD is an industry driven by the uses people put to it, for example, automotive, plastics, instrumentation, electronic fabrication, etc. It has no focus of its own.

7.2. What's important for CAD education

The following are mentioned in the survey as important in CAD education.

- the ability to formulate the engineering problems:

  In my experience as a CAD software developer (core geometry, mostly) the most important skill seems to be problem formulation. It helps to analyze problems by asking the following questions: what is the user trying to do? How we can make it easy for him? How this can be generalized?

- the ability to use a computer in solving engineering problems:

  Generally CAD curriculum is part of the engineering curriculum and has little to do with computer science. It is generally based on problem solving (mechanical engineering problems) using the computer. Many schools just teach the mechanics, which is just silly. The real lesson should be how to use the computer to solve problems and how that fits into the (much) larger engineering problem solving picture.

- a good understanding of the design process and PLM technologies:

  I have a computer science degree from MIT with a concentration in computer graphics and have taken various graduate courses over the years to keep up-to-date in computer science. I have nearly 30 years experience in the CAD/CAM industry as a CAD software developer and manager. I believe the biggest missing factor in education for software development for CAD has been in understanding the application for which the software is being developed. So, while I believe a CAD software developer should have a strong grounding in mathematics and computer science, I think it is also important for them to have a good understanding of the engineering design process, and emerging technologies used to manage the design/manufacturing product life cycle.

- practice: the most important thing for CAD

  There is nothing more important than going from start to finish with the creation of a small assembly, even if it is only three parts or so. Design the parts in the context of an assembly. Create drawings of the assembly so that others can remake the same parts with only the drawings. Cut the parts on both a lathe and mill and put them together. It sounds simple, but it is not.

8. Conclusions

To find out what CAD related topics should be taught for students in colleges and universities from an industrial perspective, we conducted a survey with selected questions, which we think are most important. The survey results should be considered as reference only, since we do not have a very large survey sample set, and the survey participants are mostly CAD vendors.

Although the training and learning needs for each person is heavily related to his educational background and job roles, we found that certain topics are required for all CAD people, and should be taught in the colleges and universities. Other topics should be taught in more advanced courses for students with specific career interests. To what extents these common knowledge and skills should be offered differ greatly from college to college, university to university, and scientific/engineering discipline to discipline. Below is a list of common topics:

- Mathematics:
  - (a) vector and matrix algebra
  - (b) analytic curves and surfaces;
  - (c) concepts of intersections and Boolean operations.
- Computer science: basics of
  - (a) computer hardware;
  - (b) Internet technologies;
  - (c) database technologies.
- Design methodologies:
  - (a) top–down/bottom–up design methodology;
  - (b) parametric modeling technologies;
  - (c) feature-based modeling technologies;
  - (d) model based design technologies;
  - (e) concepts of
    - (i) concurrent engineering;
    - (ii) network-centric collaborative design;
    - (iii) PDM, PLM and ERP.
- CAD system evaluations:
  - (a) application domains/industrial sectors;
  - (b) strength/weakness of CAD systems;
  - (c) ability to set up criteria and benchmarks for CAD system evaluations.

Notice that topics such as NURBS and B-Reps are missing from the list, while concepts such as PLM and CAD system evaluation issues find their way into the list. This may sound a little bit surprising to the geometric modeling community. However, if we look at the list very carefully, we will find that it is exactly a mirror image of what a participant said:

> CAD is just a communication tool for engineers. It does not do their job or make them better engineers. It does help them with their task at hand.

The above topics may be included in CAD related curriculums offered to undergraduate students, especially for those in computer science and mechanical engineering majors with career intention as CAD users.

For those graduate students in computer science and mechanical engineering majors with career intention as CAD application developers or advanced CAD users, more advanced CAD courses may be offered. In addition to the above, the following topics should also be included in the courses:

- Mathematics:
  - (a) advanced vector and matrix algebra; advanced optimization techniques;
  - (b) basics of
    - (i) differential geometries;
    - (ii) NURBS curves and surfaces;
    - (iii) shape interrogation.
  - (c) B-Reps and CSG.
- Computer science:
  - (a) deep knowledge on vendor-provided APIs and VBA;
  - (b) basics of C/C++ and data structures.
- *Design methodologies*. Advanced knowledge on
  - (a) parametric modeling technologies;
  - (b) feature-based modeling technologies;
  - (c) part family design.

For graduate students in Mathematics and Computer Science majors who may become CAD researchers or CAD system developers after their graduations, comprehensive CAD courses may be offered. Included in the comprehensive CAD courses are:

- Mathematics:
  (a) comprehensive vector and matrix algebra; comprehensive optimization techniques;
  (b) advanced differential geometries;
  (c) intersection and Boolean algorithms;
  (d) advanced NURBS curves and surfaces;
  (e) B-Reps and CSG;
  (f) advanced knowledge on shape interrogation;
  (g) basics of constraint solvers.
- Computer science:
  (a) deep knowledge on vendor-provided APIs and VBA;
  (b) comprehensive knowledge on C/C++ and data structures.
- *Design methodologies*. Comprehensive knowledge on
  (a) parametric modeling technologies;
  (b) feature-based modeling technologies;
  (c) model based design technologies.

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