What we are teaching in Introduction to Computer Graphics

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Figure 1: *Word Cloud of topics taught in 20 introductory computer graphics courses from around the world, following the Eurographics logo.*

Abstract

Computer Graphics is a very active field, with new knowledge being published every day at a high rate. There is, therefore, some pressure to regularly review our teaching contents and adjust accordingly. Among the courses on a standard curriculum, the introductory computer graphics course is very often the door for students into the exciting area of computer graphics. It is also the opportunity to attract and engage the best talent for the field. In this paper, we address the question of what we are teaching in the introductory computer graphics course as a community. Our main motivation was to find out how our peers are teaching this first course and use this knowledge to ease the redesign of our introductory course. We have surveyed 20 introductory computer graphics undergraduate courses from higher level educational institutions from around the world. Our source of information was purely online available resources, such as the weekly list of topics, usually provided by the professors themselves. We gathered and processed this data using a bottom-up approach. The final top level list of subjects and percentages for the introductory computer graphics courses is as follows: Rendering (75%), Modeling (14%), Animation (7%), Fundamentals (3%), and Visualization (1%). Although there is a common body of knowledge and proposed standards for an introductory course in computer graphics, we also noticed considerable variation among institutions. We believe this survey will be helpful for institutions considering designing a new introductory course from scratch or redesigning an existing one.

Categories and Subject Descriptors (according to ACM CCS): Computers and Education [K.3.2]: Computer Science Education—

1. Introduction

As in any dynamic and relatively new field, computer graphics benefits from new knowledge being published every day. Considering only six well-known journals in the field (ACM TOG, Comp. Graphics Forum, IEEE TVCG, IEEE CG&A, Computers & Graphics and The Visual Computer), we as a community publish an average of 2.75 papers a day (in Appendix A we present this data). This high production also means some pressure on curricula to cope appropriately and respond to continuing developments in the field. Therefore, as teachers and professors of computer graphics, we are always striving for the balance between breadth of coverage against depth, between a more hands-on approach versus a more theoretical

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perspective, and other balancing decisions. Within our university, we started a discussion on the prons and cons of introducing modern OpenGL in the undergraduate introductory course and the best way of doing so. This question motivated us to consider how our peer colleagues around the world were approaching the same issue. With this initial idea in mind, we thought further that it would be worth seeing what content was being taught and use this knowledge to help redesign our course.

We surveyed 20 introductory undergraduate courses in computer graphics from universities distributed on three continents (North America, Europe, and Asia) selected according to their publication records. We gathered data on the topics being taught according to the list of topics publicly available – typically on web pages. We also collected data on textbooks and whether or not modern OpenGL is already part of the curriculum. We hope our study will be helpful for institutions which are or will be redesigning their curricula in the near future. In Fig. 1 we illustrate the set of topics collected through our research as a word cloud summary.

2. Related Work

The importance of teaching in the field has been acknowledged as early as 1983 when a panel chaired by James Foley at Siggraph discussed curriculum practices in the yet incipient area of computer graphics [FBB*83]. In 1986 Ohlson advocated a stronger position for computer graphics within computer science [Ohl86], considering the lack of computer graphics content in the standards at the time. Another panel in Siggraph 1994 [BLRH*94] discussed several viewpoints on how to teach an introductory computer graphics course, bringing together professors from arts, engineering, and computer science to present their views. Jensen and Van Nieuwenhuizen [JN95] presented how computer graphics courses were offered at Delft University of Technology. In 1997 Hansmann presented a survey of computer graphics teaching in German universities, including technical universities [Han97]. The survey asked questions about computer graphics education in general, including the topics being taught.

In the late 90s and early 2000s, mainly due to the availability of OpenGL, introductory computer graphics teaching saw an increase in research activity. In a panel in 1999 during SIGCSE [HCGW99], the members proposed a philosophy for the beginning computer graphics course, expressed as a series of recommendations. Among these the recognition that computer graphics deals with intrinsically visual content, and the importance of interactivity. In [Wol00] Rosalee Wolfe presented a small survey conducted during Siggraph 1998 among 20 educators from various institutions around the US. The results are a clear picture of the state-of-the-art of teaching undergraduate computer graphics courses at the time. Among other conclusions, the number of identified unique topics was 38, and the most cited topic was viewing transformations, 95% of educators mentioned it.

Considering the interdisciplinary potential of computer graphics, Steve Cunningham presented in 2000 two papers that argued for a wider audience for the beginning computer graphics course [Cun00a, Cun00b], for instance, majors in other fields such as engineering and mathematics. Hitchner and Sowizral [HS00] proposed a new method of teaching computer graphics with a focus on intermediate and high-level principles, algorithms, and tools, as opposed to the low and intermediate levels from the past. Bouvier advanced a proposal for the introductory course blending what he called "old" (2D) and "new" (3D) topics [Bou02].

In 2004 a report from the working group on computer graphics in computer science from Siggraph and Eurographics put forward the concept of computer graphics for all [CHLS04], considering, among other aspects, the growing availability of cheaper graphics hardware in computers for domestic use. In the same year, Sung and Shirley defended that more mature students would benefit from a top-down approach for the introductory course [SS04]. Cunningham advocated the use of contexts in the beginning course as a strong motivational tool to attract and retain students [Cun08]. Low-level APIs such as OpenGL require considerable programming until compelling visual results are possible. This drawback motivated the use of the Processing language in an introductory course at the United States Air Force Academy [SBG10]. The availability of GPU programming and pervasiveness of graphics cards, motivated proposals for teaching shader-based introductory computer graphics course [AS11].

Considering the need for modern OpenGL programming skills, Fink, Weber, and Wimmer presented a framework for teaching an introductory computer graphics course at the Vienna University of Technology [FWW13]. The course has only programming assignments which guide the student through the concepts and supporting lectures given in a previous semester. Shesh reported the development of an undergraduate course at the same institution over a five semesters span [She13]. The paper provides guidelines that can be used by small and medium-sized institutions where typically only one graphics course is offered. Very recently, Ackermann and Bach [AB15] presented their experience redesigning a computer graphics introductory course. The trigger factor was how to incorporate modern OpenGL in the curriculum, the same trigger at our institution.

Our work is similar in principle to the surveys from Hansmann for German universities [Han97] and from Wolfe for US educators collected during Siggraph 1998 [Wol00]. Ours revisits the issue of content for an introductory computer graphics course, but with a broader scope, including courses from all over the world.

2.1. Standards

Besides the contributions above, our field has also seen the effort of IFIP, ACM and IEEE in providing standards to help and ease curriculum design. The first proposal was presented in 1968 [ACH*68] and already included reference to computer graphics inside one of three major divisions called "Methodologies". In 1976 a working group from IFIP discussed issues related to methodology and standards [GT76]. New updates from ACM were published in 1979, but it was only in 1991 that a major new proposal was put forward and which became known as the ACM/IEEE Curriculum 91 [acm91]. A major difference from previous standards was that this was the first proposal jointly developed by both ACM and IEEE. In this proposal, computer graphics appears inside a cluster of two courses called "Human-Computer Communication", together with "User

Interfaces". Ten years later a major revision of the Curriculum 91 was undertaken [ACM01]. In this review, the body of knowledge of Computer Science was divided into 14 areas, with "Graphics and Visual Computing" one of them. A review of the 2001 proposal was carried out in 2008 [ACM08] and a major comprehensive new version presented in 2013 [JTFoCCS13]. This is the most updated version that expanded the 14 knowledge areas into 18. In this last proposal the area "Graphics and Visual Computing" was renamed to "Graphics and Visualization". Later, on Sec. 3 we will explain how we used this last standard in our work.

3. Methodology

In this section, we descibe our methodology to collect the data. All our collected data is available at `http://wiki.inf.ufrgs.br/What_we_are_Teaching_in_Introduction_to_Computer_Graphics`.

3.1. Selection of Universities and Courses

To select the universities for our survey, we considered an almost universal assumption that the quality of research being developed correlates positively with the quality of teaching. Although some research suggests that there must be effective instruments in place to promote the synergy between teaching and research [PFB07], it is generally accepted that there exists an indirect benefit between strong research and quality of teaching [Kha17].

In order to compute the institutions which are doing the high impact research in computer graphics, we have surveyed the last two editions (2015/2016) of Siggraph, Siggraph Asia, and Eurographics, easily recognizable as venues where high-quality research is published. For each paper, we collected the names of institutions affiliated with that paper, but only for higher educational institutions that grant undergraduate degrees. If a given paper had more than one affiliation, each author received a share of the total. For instance, a paper with three authors from three different institutions would receive $1/3$ authorship each. When the authors listed two or more affiliations, and at least one was with an educational institution, we used his/her first affiliation with the educational institution. We understand that this introduces only a small bias due to the low number of such cases. Also, when two departments of the same university are listed, we grouped them as being the same. The final list has unique 224 institutions. We decided to use 20 for our survey since it is approximately 10% of the total number.

In Table 1 we list the 20 institutions ranked higher together with the number of papers they published. Fig. 2 illustrates how these institutions are geographically located. It is important to mention that some institutions do not appear here either because they do not grant undergraduate degrees or did not have online information available.

For each university on this list, we visited their web pages of the computer science courses and searched for the introductory computer graphics course available for majors in Computer Science. This was our primary source of data from which we collected the following: *(i)* learning topics; *(ii)* textbook; *(iii)* information about modern OpenGL. In only one case we used an automatic translation of the content.

Institution	Number of papers
Stanford	18.89
MIT	16.32
Univ. British Columbia	12.21
ETH Zurich	11.55
University College London	7.83
Columbia University	7.51
The Chinese Univ. of Hong Kong	7.03
Univ. Southern California	6.19
Tsinghua University	6.02
Princeton	5.60
Carnegie Mellon	5.52
RWTH Aachen Univ.	5.37
The Univ. Hong Kong	4.85
Tel Aviv Univ.	4.67
New York Univ.	4.58
Cornell	4.48
TU Wien	4.47
Univ. of Science and Technology of China	4.38
University of Wisconsin (Madison)	4.32
KAIST	4.27

Table 1: *Higher ranked 20 institutions according to the number of published papers in the last two editions of Siggraph, Siggraph Asia, and Eurographics (only higher level educational institutions).*

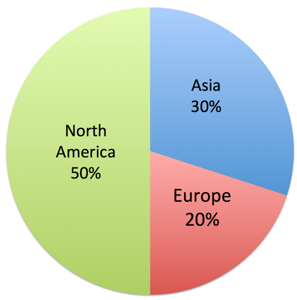

Figure 2: *Distribution of the 20 institutions according to the continent.*

We think that the use of the online list of learning topics for each class, maintained by the instructors of the courses themselves, is a reliable source of information since it is easier to update and edit, and likely reflect the current state-of-practice. From our list of 20 institutions, 12 had information from 2016, five from 2015, one from 2012, and for two institutions we could not accurately establish the last update. Although it would be preferable to have all information from 2016, we consider that the overall set is still representative of current practice.

We included in Table 2 the titles of courses for reference. The most common one is simply *Computer Graphics* with half of the titles, although other possibilities appear.

Name	Number of occurrences
Basic Techniques in Computer Graphics	1
Computer Graphics	10
Introduction to Computer Graphics	4
Fundamentals of Computer Graphics	1
Fundamentals of Computer Graphics, Image Processing, and Vision	1
Interactive Computer Graphics	1
Introduction to Computer Graphics and Imaging	1
Visual Computing	1

Table 2: *Names of courses and occurrences.*

3.2. Main topics being taught

From the 20 institutions, we collected the learning topics and an associated counter for each topic. The counter expressed how many times a given topic appeared. If a given course has three classes on "ray tracing", for instance, we counted as three occurrences instead of one. We think this expresses the weight of the topic on the course as a whole. We call this initial set the *raw* set since semantically similar entries are treated as distinct. For instance, *raytracing* and *ray tracing* are two separate entries. We processed the raw set for lexically similar topics as in the ray tracing example, generating our level 0 set of topics. As expected we collected a large number of different topics, 277 to be exact. In Table 3 we list the 10 most cited topics from the level 0 set.

	Topic	Number of occurrences
1	Ray Tracing	17
2	Texture Mapping	17
3	Rasterization	15
4	Graphics Pipeline	11
5	Transformations	10
6	Global Illumination	9
7	Lighting and Shading	9
8	3D transformations	8
9	Clipping	8
10	Animation	7

Table 3: *Top 10 topics in the level 0 set of topics.*

Although the level 0 set is a very rich source of information, we also need a higher level view of the topics. The next step was therefore to process the level 0 set bottom-up to create a hierarchy of topics, by clustering lexically and semantically similar topics. Although automatic clustering methods could be used, we estimate that a manual clustering would be useful for a first approximation, even more considering the difficulties in establishing good distance metrics for clustering in this context. Therefore we manually processed the entries in the level 0 set to compute the clusterings, considering our 20 years experience of teaching the introductory computer graphics course. In Table 4 we show the level 1 set of 24 clusters as a result of our clustering on the level 0 set.

As expected, "Graphics Pipeline" appears as the main cluster. This cluster includes basically the topics *viewing transformations*, *clipping*, and *visibility*. Some topics which are also taught as part of the graphics pipeline were listed separated, due to their high number of occurrences. This is the case for clusters "Transformations", "Lighting and Shading", and "Rasterization". Also as expected, clusters with lower occurrence are typically present in more advanced courses, not necessarily the introductory one. Among these, we mention "computer vision" and "visualization". Curiously, GPU appears with less than 1%. Maybe this topic is given in laboratory classes, not necessarily as lectures. The "Miscellaneous" cluster gathers all topics which are not clearly part of any of the other clusters. Examples of topics in the miscellaneous cluster are *history of computer graphics* (only one occurrence), *deep learning* (2 occurrences), and *image-based rendering* (one occurrence). In the "Applications" cluster we included topics such as *3D printing* and *non-photorealistic rendering*. The "Tools" cluster lists helpful tools such as *Matlab*, *Maya*, and *SolidWorks*.

	Topic	Number of occurrences	Percent
1	Graphics Pipeline	79	15.4%
2	Geometric Modeling	62	12.1%
3	Global Illumination	38	7.4%
6	Transformations	36	7.0%
4	Lighting and Shading	33	6.4%
5	Ray Tracing	31	6.1%
7	Animation	30	5.9%
8	Rasterization	30	5.9%
9	Texture Mapping	24	4.7%
10	Misc	16	3.1%
11	Shaders	16	3.1%
12	Sampling	15	2.9%
13	Image Processing	13	2.5%
14	Color	12	2.3%
15	OpenGL and WebGL	12	2.3%
16	Applications	11	2.1%
17	Hierarchical Modeling	10	2.0%
18	Shadows	9	1.8%
19	Interaction	8	1.6%
20	Tools	8	1.6%
21	Math Review	6	1.2%
22	Computer Vision	5	1.0%
23	GPU	4	0.8%
24	Visualization	4	0.8%

Table 4: *Level 1 clusterization of topics.*

Now that we have the level 1 clusters, we can map back to the universities and see what the "coverage" of a given topic among all institutions is. In Table 5 we list the level 1 clusters and the percent of universities that have these topics explicitly in their web listings. From this table, we can see for instance that "Graphics Pipeline" and "Rasterization" are very popular topics whereas "Computer Vision" appears in only 10% of the surveyed universities. When designing a new course or redesign an existing one, the information in this table indicates the importance of topics as expressed by these universities in their introductory computer graphics course.

Clustering yet again the contents of Table 4 we achieve the level 2 set of clusters shown in Table 6. As a semantic guide for this last

	Topic	Percent
1	Graphics Pipeline	95%
2	Rasterization	95%
3	Lighting and Shading	90%
4	Ray Tracing	90%
5	Geometric Modeling	85%
6	Texture Mapping	85%
7	Global Illumination	65%
8	Transformations	65%
9	Animation	55%
10	Shaders	55%
11	Color	50%
12	Misc	45%
13	Sampling	45%
14	OpenGL and WebGL	40%
15	Hierarchical Modeling	40%
16	Image Processing	30%
17	Applications	25%
18	Shadows	25%
19	Tools	25%
20	Interaction	20%
21	Math Review	20%
22	GPU	20%
23	Visualization	15%
24	Computer Vision	10%

Table 5: *Percentage of Level 1 clusters taught by Universities.*

Topic	Percent
Rendering	75%
Modeling	14%
Animation	7%
Fundamentals	3%
Visualization	1%

Table 6: *Level 2 clusters.*

Name	Number of occurrences
Peter Shirley [MS16]	3
Steven Gortler [Gor12]	3
Edward Angel [Ang08]	3
Hearn, Baker, and Carithers [HBC10]	1
M. Slater, Y. Chrysanthou, A. Steed [SSC01]	1

Table 7: *Textbooks used.*

clustering, we used the five knowledge units listed in the most recent standard proposed by ACM and IEEE [JTFoCCS13] under the knowledge area “Graphics and Visualization”: Fundamentals, Rendering, Modeling, Animation, and Visualization. We can see that “Rendering” is responsible for 75% of the contents. At first, it appears excessive, but “Rendering” represents the core of what we do, and therefore for a typical introductory computer graphics course this amount seems appropriate to us. Concerning the percentage given to the other topics, if we recall that the ACM/IEEE standard is for the knowledge area as a whole, not only for the introductory course, we think that the distribution is appropriate. In a way, this higher level clustering is the snapshot of current state-of-practice of the 20 institutions we surveyed.

Out of the original 277 level 0 topics we collected, almost 20% of topics could not be mapped to the ACM/IEEE standard. Again, this is not so surprising since many topics in the courses we surveyed are beyond a typical undergraduate introductory course. Topics such as “Image Processing” and “Interaction”, just to mention two, appear in the ACM/IEEE standard under another knowledge area, not “Graphics and Visualization”.

3.3. Textbooks

Another information we gathered refers to the use of a textbook. Of the 20 surveyed institutions, 11 mentioned textbooks, and of these, 9 mentioned as required. The used textbooks are listed in Table 7.

3.4. Modern OpenGL

Modern OpenGL was introduced in version 3.3 of OpenGL, in 2008. All fixed functions were deprecated, favoring the use of shaders and the introduction of GLSL - OpenGL Shading Language. All teaching using OpenGL was affected by this change. The so-called modern OpenGL is more complex to teach and learn and therefore many courses still use the legacy mode version. The decision on when and how to change is still in discussion by the community [AB15]. Of the 20 surveyed institutions, 11 mention modern OpenGL in their topics or assignments. Unfortunately, we could not gather more precise information from only online resources. This means that we do not know precisely if the other nine universities do not teach modern OpenGL or that simply this information was not available online. At any rate, 55% of the institutions teach modern OpenGL. Considering this scenario, an effort to ease the transition to modern OpenGL as presented by Reina, Müller, and Ertl [RME14] is welcome.

4. Discussion

The only two previously available surveys [Han97, Wol00] reported a significantly lower number of topics. In both, the educators had to choose topics from an existing list, 34 and 38 topics respectively. Our survey reported a much higher number of topics, and we think this is due to two reasons. First, we collected the data directly from online resources; there was no list to choose from. Second, in the 16 years since the last survey, our field has grown significantly. Today maybe it would be difficult to agree on a comprehensive list of topics if we were to repeat the methodology of the previous surveys.

In general, courses balance theory with applications and technology and it is interesting to see how this balance evolved over time. The two previous surveys also offer us a view on what was “hot” at the time and maybe it is not so hot anymore. For instance, in both surveys *Fractals* appear as a relatively significantly topic, whereas in our survey there is no mention to Fractals. Also, in the survey of German universities, there is a topic called *Product Data Exchange*, a standard for information exchange among CAD systems. Clearly, today's undergraduate courses would not teach such a technical topic.

Another interesting aspect concerns textbooks. The classic Foley *et al.* book [FFHD90] disappeared from current teaching whereas a previous edition of Angel's book [Ang08] is already mentioned in the US survey. Although our field has a good collection of excellent references, it appears that approximately half of the instructors still rely mostly on course notes provided to the students. Considering the relatively young age of Computer Science when compared with other fields such as Physics and Mathematics, maybe we as a community do not have yet a consensual view of what an introductory course should offer, and this impacts the use of textbooks.

Finally, regarding modern OpenGL, our survey suggests that it is a hard topic to include in teaching, given that it has been around since 2008 and our data suggests that only half of the institutions are clearly teaching it. It is not surprising therefore that some institutions are switching to higher-level approaches such as WebGL [AB15].

5. Conclusions

We have presented a survey of Introductory Computer Graphics courses from 20 higher learning institutions from around the world. From these courses we collected data on which topics are being taught, the textbook used, and whether these courses are already teaching modern OpenGL or not.

The source of our survey was the list of topics publicly available. We realize that there are intrinsic limitations to this source, since it is not clear whether or not instructors are following these listings. Also, the criterion for selection of the surveyed institutions with its emphasis on research leaves out of the results many medium and small-sized high-quality educational institutions. It would be worth pursuing a survey similar to ours but over a larger sample of schools. Nevertheless, we think the collected data and clustering here presented should be useful for institutions looking into redesigning their curricula.

For future work, we would like to add more courses to our survey and then run an automatic or semi-automatic bottom-up hierarchical clustering algorithm, to compare with our clustering.

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Appendix A: Number of published papers in 2016

In order to estimate the strength of the Computer Graphics area as a whole, we gathered data on the number of papers published in the top 6 journals in the area according to their impact factor. The total number of papers (1003) is given in Table 8. Dividing this total by 365 we have the average of 2.75 papers a day. Data gathered from the DBLP database.

Journal	volume	Number of papers
ACM TOG	35	250
Comp. Graph. Forum	35	238
IEEE TVCG	22	233
IEEE CG&A	36	56
Comp. & Graphics	54-61	97
Visual Comp.	32	129
Total		**1003**

Table 8: *Number of papers published in 2016 in the top 6 journals of the field.*

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