Introducing TCAD Tools in a Graduate Level Device Physics Course

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***Abstract*—The impact that project complexity, student prior academic achievement, and quality of instructional materials might have on student academic achievement was studied during a required device physics course, in which technology computer-aided design (TCAD) tools were introduced to first-year graduate students. Preliminary analysis of student performance and project complexity showed that students who attempted the most complex projects had the lowest student academic achievement, despite there being no significant differences in prior academic achievement as measured by grades in the first exam in the course. Further analysis of student achievement data from other electrical engineering courses taught in a similar open laboratory format, for which enhanced instructional materials were developed, suggest that when well-developed learning resources are easily accessible to students, project complexity has no negative impact on student academic achievement and can sometimes enhance student academic performance. Cognitive load theory was used to explain why well-developed instructional tools, such as enhanced tutorials, can help students better learn or work with complex material.**

***Index Terms*—Cognitive load theory, device physics, education, graduate students, technical computer-aided design (TCAD).**

I. Introduction

Technical computer-aided design (TCAD) software tools are introduced to students taking a required course in semiconductor device physics in the electrical engineering (EE) department of San Jose State University (SJSU), San Jose, CA. All EE graduate students are required to take this course, which is a prerequisite for all graduate full-custom analog and digital circuit design courses offered by the EE department, as well as for follow-up courses in device physics and semiconductor processing.

TCAD tools consist of two finite element mesh (FEM) solvers. The first FEM solver parses a semiconductor process recipe and calculates the resulting structure. For instance, for a recipe that calls for a dry oxidation to be performed on a bare silicon substrate with an orientation of $\langle 100\rangle$, and a substrate doping level of 10^{16} boron atoms cm^{-3}, at 1000 °C for 30 min, the process simulator (in this case Sentaurus process) calculates the resulting silicon dioxide thickness and how the boron atoms in the substrate would be redistributed after the oxide growth step. Since modern TCAD tools take into account most known process effects, this tool is sometimes referred to as a virtual fabrication facility.

The second FEM solver (in this case Sentaurus device) uses the structure produced by the virtual fabrication facility software and simulates its electrical and optical properties. In this case, the process recipe previously mentioned produces a metal oxide semiconductor (MOS) capacitor structure. The electrical characterization software can be used to simulate a capacitance voltage sweep of this MOS capacitor, to be able later to determine the threshold voltage of the structure. Because TCAD tools help to predict accurately the electrical performance of a device created from a process recipe, the cost for developing a new device is greatly reduced.

Introducing TCAD tools to first-year graduate students is considered important at SJSU for the following reasons.

- The use of TCAD tools allows students to learn the fundamentals of device processing in a virtual environment (a more cost-effective option for exploring scenarios or testing hypotheses when compared to traditional fabrication labs) and helps them to acquire critical thinking skills while having an authentic design experience (very similar to the actual experience in research or work environments).
- Proficiency with the use of TCAD tools has become a necessity in modern manufacturing environments, particularly in Silicon Valley.
- Introducing TCAD tools in class better prepares first-year graduate students for semiconductor device research in advanced courses.

As well as being quite important, teaching TCAD tools is also a difficult task [1], [2]. For instance, apart from their expertise in the field of semiconductor device physics, instructors need to be highly competent in the specific TCAD tools used in class to be able to answer students' questions related to the class topic or the tools. Students need to be competent in areas such as grid generation, numerical methods, and semiconductor device physics to be able successfully to model and design a device using these tools. In addition, the college or department needs to provide the required learning environment, which includes ample and well-maintained computer resources to run the TCAD tools.

Operating a TCAD lab requires resources beyond that of a traditional lecture course. As a rule of thumb, minimum resources include: a UNIX type server for every five students,[1] software license/updates (costs ranging from $2500 to $5000 each year),

Manuscript received August 2, 2007; revised December 26, 2007. First published June 17, 2008; last published August 6, 2008 (projected).

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Digital Object Identifier 10.1109/TE.2008.916765

[1]Students can remotely log into the UNIX machines from their personal computers. Based on usage patterns at SJSU for the past five years, a five user to machine ratio gives acceptable performance.

and IT support to manage user accounts.[2] Instructors may also need to allocate time for learning the tools and developing instructional materials, such as enhanced tutorials.

When external support is not available, the cost of implementing and maintaining TCAD tools may seem prohibitive for programs with small enrollment. However, there might be more significant costs associated with not using TCAD in semiconductor device instruction because teaching semiconductor device physics using a traditional processing lab is usually much more expensive than operating a computer lab [3], [4]. For example, at SJSU's College of Engineering the microelectronics processing lab teaches approximately 80 students per year at a cost of \$140 000, including a full-time technician. In comparison, the computer lab serves over 200 students at a cost of \$55 000, which includes software and a half-time IT employee.

In sum, investing in TCAD tools in device physics courses is becoming a necessity for many EE programs that strive to provide their students with critical skills in this field. This endeavor nevertheless requires a serious investment and may significantly increase the teaching and learning load for instructors and students, respectively. Such a serious investment also makes it necessary to identify and study factors that may play a role in the students' learning experience. This information could then be used to prevent students from being overwhelmed by, and ultimately discouraged from, undertaking challenging projects. Students may come to perceive that learning the TCAD tools is in itself complicated enough, and thus may try to avoid challenging projects that could further enhance their engineering education.

In this paper, the relationship between student academic achievement and class project complexity is studied, after taking into account students' initial academic achievement and quality of learning resources, such as the availability of enhanced TCAD tutorials. In the following sections, a description of the semiconductor device physics course taught in the EE Master's program at SJSU (in which first-year graduate students were introduced to TCAD tools) and its learning environment are provided, including some of the problems associated with teaching these tools and how these were addressed. Cognitive load theory [5] was used to explain the findings regarding the relationship between project complexity, student academic achievement, and quality of learning resources, and to draw conclusions based on these results.

II. Course Details

EE221, Principles of Device Physics, is a one-semester, three-credit hour required course for all graduate students enrolled in SJSU's Masters of Electrical Engineering program. The course topics are typical of a graduate-level course in device physics, and are designed to support the course aims and objectives, as described below.

The course aims to prepare graduate students as follows:

- for a career in circuit (analog or full custom digital) design;
- for further studies in device physics;
- to be able to make technology decisions based on science.

The course learning objectives are that students will be able to achieve the following:

- intuitively explain semiconductor device phenomena;
- use analytical and TCAD models for device fabrication design, including the development of a Spice Level 3 MOSFET model from measured data;
- understand the device issues relating to analog and digital CMOS circuit design;
- explain MOS subthreshold behavior.

To support these aims and learning objectives more effectively, going beyond the possibilities offered by traditional lecture type courses, TCAD tools were introduced. The tools were in an open lab environment in which students could use the software independently, and outside course/session hours. The main advantages of having the students learn in an open lab setting were that this better replicated industrial design settings, and improved the cost effectiveness of the course [6]. Besides independent lab work, the students received help during office hours and through e-mail communication with the instructor. The final class grade was based on homework assignments (10%), two midterm exams (17% each), a final exam (36%), and a class project (20%).

III. Learning Environment

The students were from one section (fall 2006) of EE221 (38 total students), and were in their first year of graduate studies in SJSU's Master of Electrical Engineering (M.S.E.E.) program. Most students in the course were international and, based on previous graduate student surveys,[3] SJSU's proximity to Silicon Valley had a significant influence on their decision to attend the college. While the majority of students surveyed showed interest in obtaining a job in local industry right after graduation, some students showed an interest in continuing their education at the doctoral level [7]. Given that this survey represented the graduate population fully, it is inferred that the students enrolled in this course mostly came so that they could profit from the opportunities provided by Silicon Valley, and that some would want to continue their studies after obtaining their M.S.E.E. degree at SJSU.

The course lab had 25 Dell Linux workstations and 25 HP Linux workstations. Each workstation had a 3 GHz CPU with 2 GB of RAM, which satisfied all hardware requirements for the lab implementation. The TCAD software was Synopsys's Sentaurus: Sentaurus process was used for process modeling; Sentaurus structure editor was used for mesh refinement; and Sentaurus device was used for electrical simulation.

The lab had one technician (half-time) who configured the computer system, handled account requests, and made data backups. Installation and verification of TCAD tools was done by the course instructor.

As part of the course, students were introduced to the TCAD tools during class demonstrations by the instructor. Students continued with the instruction by following tutorials provided by Synopsys [8] or tutorials developed inhouse [9], which were assigned for homework. These tutorials were critical to the learning environment because they were designed with the purpose of enabling students to learn the material independently in an adaptive learning environment (i.e., learning at their own pace, addressing areas of need). The enhanced tutorials

[2]The cost of an IT person can be hard to scale to need. Having one machine or 100 machines makes little difference to the workload for an IT person skilled in scripting.

[3]The survey included beginner and graduating graduate students in both required and elective courses.

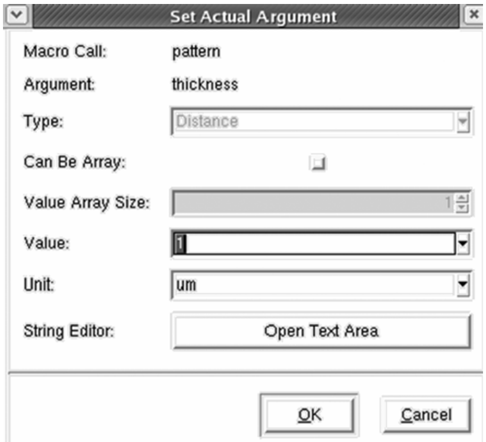

Fig. 1. Sample POPUP window in the Sentaurus TCAD process editor.

```
machine clear
mgoals on
set sim_left 0
set sim_right 2
set sim_bottom 5
set sim_top 0
## ------------------------------------##
## --------  LIGAMENT OUTPUT  --------##
## ------------------------------------##
## ------ Ligament defined grid ------##
## ------------------------------------##
line y loc=0 spa=0.4 tag=left
line y loc=2 spa=0.4 tag=right
line x loc=0 spa=0.25 tag=top
line x loc=5 tag=bottom
region Silicon xlo=top xhi=bottom ylo=left yhi=right
init concentration=1e16 field=Boron wafer.orient=100  slice.angle=[CutLine2D 0 0 2 0]

## ------------------------------------
## ---- Added process flow header -----
## ------------------------------------
deposit material = {Oxide} type = isotropic Phosphorus conc=5e21 rate = {1.0} time=0.3
temp_ramp name=tempramp_1_2 time=60 temp=900
diffuse temp_ramp=tempramp_1_2
mask name=mask_1_2 segments = {1.0 2.1 } negative
photo mask=mask_1_2 thickness=1
struct smesh=n@node@
exit
```

Fig. 2. Sample converted Sentaurus process code.

(developed inhouse) not only described the software tool in detail, but also addressed course learning objectives, such as the review of worked examples [10].

One of the enhanced tutorials (developed by the researchers) used during the course was the diode tutorial, in which students learn the Sentaurus package by virtually fabricating a diode, and electrically testing it using the Synopsys TCAD tools. The tutorial used graphics as the main component of instruction—they showed each step students had to complete throughout the process along with the expected results. For instance, the tutorial had students fill out a graphics "popup" (as in Fig. 1) to apply and then pattern photo resist. Then, the tutorial showed the code generated from the "popup" (Fig. 2), followed by the results of the virtual processing steps (Fig. 3).

The TCAD projects were completed according to the following time frame. By class 5 of the course (of a total of 32 classes), students had learned the basics of TCAD by following the tutorials provided by Synopsys. For class 6, students had selected their partner (the maximum group size was 2) and the topic for their group project, which they were encouraged to choose to increase their awareness of their own skills and deficiencies in learning. (NOTE: suggested edits.) By class 10,

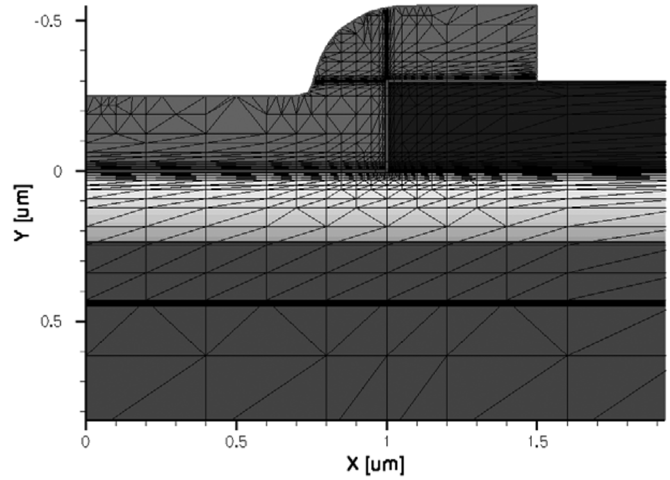

Fig. 3. Sample TCAD result (diode) from Sentaurus process code.

students learned how to run a simple diode processing and electrical extraction TCAD example. A literature review was due by class 15, and in class 23 student ran the N-type metal–oxide semiconductor (NMOS) processing and extraction example. The project report was due on the last day of instruction.

The complexity of selected projects ranged from the very simple (solar cells) to the very complex [GaN high electron mobility transistor (HEMT) structures]. As part of the instruction, three design reviews were held throughout the semester, including a one-on-one discussion of the literature review of the project with the instructor during office hours.

IV. Results and Discussion

By the end of the semester, the instructors noticed that students who had attempted more complex projects, such as laterally diffused metal oxide semiconductor (LDMOS) or HEMT structures, showed lower academic achievement (as measured by class grades) than students who chose simpler projects. This might seem somewhat counterintuitive or disappointing to some observers, for complex projects should have afforded students more opportunities to learn more than just the "basics," compared to their counterparts attempting simpler projects.

To test these conjectures, based on simple observations, regarding the relationship between project complexity and skills attainment or academic achievement, the 38 students in the course were aggregated into four groups based on the complexity of their group project. Students in group 1 (12 or 32% of the class) included those who worked on projects such as solar cells and MOS capacitors; group 2 (14 or 37%) had students with projects such as modifying the Synopsys NMOS example; group 3 (5 or 13%) had students with projects such as process modeling and electrical simulation of SJSU's inhouse NMOS processes [11]; and group 4 (7 or 18%) had students with projects such as modeling LDMOS and HEMT structures. Group means for the project grade, final exam, and final course grade were calculated for each group as a measure of academic achievement, and then plotted by project complexity (Fig. 4).

As can be seen in Fig. 4, the academic achievement means for students in the complex projects (group 4) were significantly

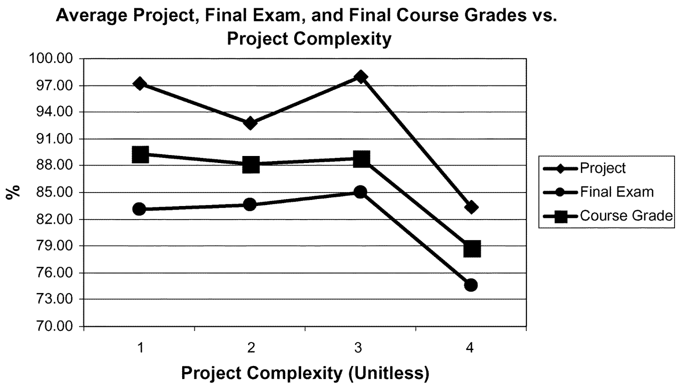

Fig. 4. Average project, final exam, and final course grades versus project complexity for a required graduate semiconductor device physics course.

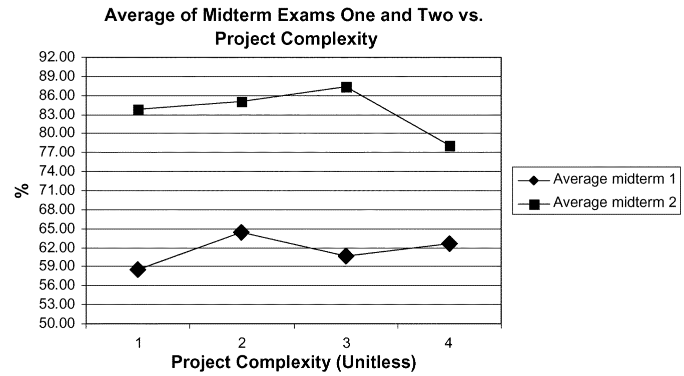

Fig. 5. Average midterm 1 and midterm 2 grades versus project complexity for a required graduate device physics course.

lower than comparable means for the other groups. Students in group 4 had an average final course grade of 79% (C+), as opposed to the other groups which had an average final grade of 88% (B+). Students in group 4 scored much lower on both the project and final exam.

These findings suggested that students who worked on the more complex projects did not learn as much as those who worked on less complex projects. Understanding these results was important to the researchers because using TCAD tools was resource-intensive, and all students should benefit from their use. Also, the instructor wanted to avoid the scenario of students refusing to attempt complex projects to avoid receiving a lower course grade. Cognitive load theory (CLT) and data from courses taught in a similar format were used to study these findings further.

Cognitive load theory [5] models the human mind as an information processing system with limited resources. One of these limited resources is called *working memory*—a person can concentrate only on a limited number of concepts at a time before the working memory becomes overloaded. A student with overloaded working memory will have major difficulties processing information or learning new concepts. Since learning TCAD tools and the course subject matter involves many new and complex concepts (UNIX, device physics, meshing, processing), this activity is likely to overload students' working memory, particularly when working on complex projects. Attempting to model the advanced devices (requiring mastery of extra concepts such as LDMOS, or quantum based structures) while at the same time learning the TCAD tools was perhaps overwhelming to the students in group 4 and impaired their learning.

Assuming that learning TCAD tools was a probable source of cognitive overload for students in group 4, why did students in the other groups seem to have been able to handle the high demand on cognitive resources? Based on observations made by the researchers, one possible explanation to these findings is that students in the less complex projects were better prepared for the class, and were thus better able to choose a project that would provide the most efficient use of their cognitive capabilities than were students who selected complex projects. In other words, differences in entry behavior or prior knowledge might account for most of the differences in end-behavior or academic achievement across groups.

Another explanation for the better performance of the students in the less complex groups relates to the resources available to these students better to manage the cognitive demands of the tasks. Students in groups 1–3 were able to take advantage of a tutorial developed by the course instructor, which showed step-by-step how to design the processing of a diode (Sentaurus process), re-mesh it for electrical simulation (Sentaurus structure editor), simulate the diode electrically (Sentaurus device), and extract the ideality factor (inspect). This tutorial also had extensive help/documentation about the inhouse NMOS processes. This enhanced tutorial was quite detailed and had a visual for each step (over 100 figures), which might have reduced students' cognitive load, resulting in more efficient learning. Group 4 had no such example files or tutorial.

The argument that entry behaviors are what accounts for the lower performance of group 4 is not supported by data in Fig. 5, which showed no significant relationship between exam 1 (a measure of students entry behavior or prior knowledge) and project complexity. Fig. 5 also plots groups' average scores in exam 2, given at the end of the third quarter of the semester, a time by which the lower achievement of group 4 was already apparent.

To study further the relationship between cognitive load (as impacted by project complexity), instructional resources, and student academic achievement, data from a different course with a similar instructional format were analyzed. Design of CMOS Digital Circuits, EE166, had been taught in an open lab environment for over six years by the same instructor, which had allowed him to develop many enhanced tutorials and case studies for students to access through the Internet. Students in EE166 selected their projects, which relied heavily on CAD tools just like the semiconductor device physics course.

Fig. 6 plots average scores for exam 1 and final course grade by student group based on project complexity in EE166 [12]. For this "well-seasoned" course, with a stable learning environment and extensive tutorials, students in the group with the most complex projects showed the highest academic achievement, as shown by results in Fig. 6. These results cannot be explained by prior knowledge because there is no relationship between exam 1 grades and project complexity, as shown by the data. (Exam 1 covered device physics review, and was given during the second class meeting.) So far, the availability of well-developed tutorials and related instructional materials seems to be

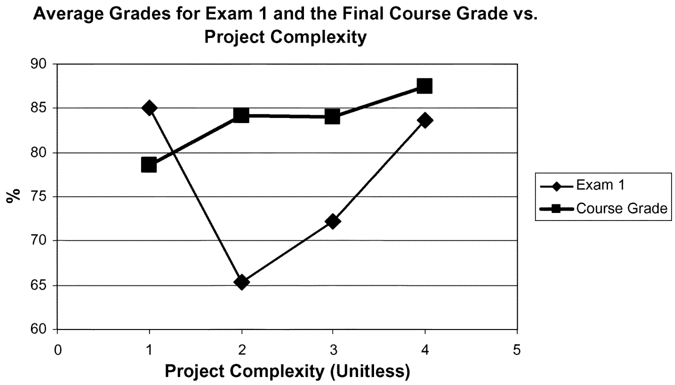

Fig. 6. Average exam 1 grade and final course grades versus project complexity for a stable CMOS digital design course.

the factor mediating the relationship between academic achievement and project complexity for EE courses using TCAD tools.

V. Conclusion

TCAD tools are an important component in modern manufacturing environments and can be an excellent resource for teaching semiconductor device physics and processing in a highly cost-effective manner. TCAD tools afford students the opportunity to work on solving authentic and complex problems—similar to those they will encounter at work or research settings.

The purpose of teaching TCAD tools in graduate courses should always be to support the teaching of content/subject matter and facilitate student learning. Instructors need to be aware that when instructional resources are not adequate, having to learn these TCAD tools may actually obstruct student learning by overwhelming student cognitive resources, particularly for students working on complex projects. For any design course that includes TCAD tools, instructors need to take into account the following guidelines.

- Tutorials provided by TCAD products need to be reviewed carefully to assess the extent to which these materials can support instruction and help students have a successful learning experience. Simplicity and clarity of instructions, use of visuals, and number of "worked-out" examples are key indicators of well-developed tutorials.
- Having students review successful projects from previous years will make them aware of the complexity involved in class projects.
- Students should be counseled not to choose complex projects unless they have adequate knowledge of TCAD tools and/or the instructor can provide students with easy access to well-developed instructional materials for TCAD tools. Students should be encouraged to develop metacognition or self-awareness of areas of strength and deficiency.
- Documentation should be provided on technologies supporting the use of the TCAD tools, such as a tutorial on using the operating system and remote login [13].
- Instructors considering using an open lab setting, rather than a traditional lab meeting time, should also consider advantages afforded by e-mail systems and the Internet. E-mail groups can be used to answer student questions and reply to the whole class, which greatly benefits those students who cannot attend office hours, or register for a three-hour laboratory period.[4] A list of frequently asked questions can also be posted in the Internet.

Acknowledgment

The authors would like to thank Synopsys and Intel for the generous donation of the Linux lab and TCAD tools. The researchers also gratefully acknowledge K. Israel, B. J. Black, and E. Crain for their IT support of the lab.

References

[1] A. Asenov and C. R. Stanley, "CAESAR: A virtual IC factory in an undergraduate semiconductor device fabrication laboratory," *IEE Colloq. Phys. Mod. Sem. Dev.*, pp. 10/1–10/6, 1995.

[2] M. Redford and E. Price, "The teaching company scheme an academic-industry partnership- A case study," in *Proc. 10th Biennial University, Government, Industry Microelectronic Symp.*, Research Triangle, NC, 1993, pp. 29–36.

[3] J. Kenrow, "Integrating professional TCAD simulation tools in undergraduate semiconductor device courses," in *Proc. ASEE Annu. Conf. Expo.: Engineering Education Reaches New Heights*, Salt Lake City, UT, 2004, CD-ROM.

[4] N. H. Kapadia, J. A. B. Fortes, and M. S. Lundstrom, "The semiconductor simulation hub: A network-based microelectronics simulation laboratory," in *Proc. 12th Biennial University, Government, Industry Microelectronics Symp.*, Rochester, NY, 1997, pp. 72–77.

[5] J. J. G. van Merrienboer, P. A. Kirschner, and L. Kester, "Taking the load off of a learner's mind: Instructional design for complex learning," *Educ. Psych.*, vol. 38, no. 1, pp. 5–13, 2003.

[6] D. W. Parent, "Using open-ended design projects in an open lab to teach lifelong learning skills in an IC design course," in *Proc. ASEE Annu. Conf. Expo.: Engineering Education Reaches New Heights*, Salt Lake City, UT, 2004, CD-ROM.

[7] D. W. Parent, San Jose State Universtiy Electrical Engineering Graduate Survey Results, Jul. 2007 [Online]. Available: http://www.engr.sjsu.edu/dparent/ee221/survey_results.doc

[8] Synopsys, Mountain View, CA, Jul. 2007 [Online]. Available: http://www.synopsys.com

[9] D. W. Parent, "Getting started with Synopsys TCAD tools," Jul. 2007 [Online]. Available: http://www.engr.sjsu.edu/dparent/ee221/sentaurus.pdf

[10] W. Mwangi and J. Sweller, "Learning to solve compare word problems: The effect of example format and generating self-explanations," *Cogn. Instruct.*, vol. 16, no. 2, pp. 173–199, 1998.

[11] D. W. Parent, EE/MatE 129, Jul. 2007 [Online]. Available: http://www.engr.sjsu.edu/~dparent/ee129/index.htm

[12] D. W. Parent, EE166, Jul. 2007 [Online]. Available: http://www.engr.sjsu.edu/~dparent/ee166/index.htm

[13] D. W. Parent, IC Group, Jul. 2007 [Online]. Available: http://www.engr.sjsu.edu/~dparent/ICGROUP/UNIX.pdf

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[4]Many students have full-time technical positions on campus.