

Development of a Circuits Class: Rethinking Traditional Teaching Methods

Claudio Talarico, Gonzaga University

Claudio Talarico received B.S. and M.S. degrees in Electrical Engineering from University of Genova, Italy and a Ph.D. degree in Electrical Engineering from University of Hawaii. He is currently a Professor of Electrical and Computer Engineering at Gonzaga University. Before joining Gonzaga University, he worked at Eastern Washington University, University of Arizona, and in industry, where he held both engineering and management positions at Siemens Semiconductors, IKOS Systems, and Marconi Communications. Dr. Talarico research interests include digital and mixed analog/digital integrated circuits and systems, computer-aided design methodologies, and design and analysis of embedded systems-on-chip.

Dr. George D. Ricco, Gonzaga University

George D. Ricco is the KEEN Program Coordinator at Gonzaga University in the School of Engineering and Applied Science. He completed his doctorate in engineering education from Purdue University's School of Engineering Education. Previously, he received an M.S. in earth and planetary sciences studying geospatial imaging, and an M.S. in physics studying high-pressure, high-temperature FT-IR spectroscopy in heavy water, both from the University of California, Santa Cruz. He holds a B.S.E. in engineering physics with a concentration in electrical engineering from Case Western Reserve University. His academic interests include longitudinal analysis, visualization, semantics, team formation, gender issues, existential phenomenology, and lagomorph physiology.

Mr. Rick M. Cox, Gonzaga University

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Abstract

Problems with teaching introductory courses in circuit analysis and design are well known and have been extensively documented over the past few decades. Inspired by a few of the researchers in the field, we have designed a collection of supplementary materials to be presented in our introductory courses. This material is designed specifically to teach students how to solve problems in a practical manner. Starting off with a reintroduction to fundamental laws (such as Kirchhoff's and Thevenin's), through addressing concepts such as zeros and poles, the material will provide students a scaffolding to use basic circuits principles and solve complex problems normally onerous to the apprentice electrical engineer. More advanced concepts such as switched capacitors circuits and broadband amplifiers are also covered. Finally, the entirety of this material is compiled for dissemination on a web page for the community at large.

1. Introduction

When one compares today's students to those of earlier generations, the differences are striking. Yet the way most faculties teach electric circuits is essentially unchanged since the middle of the last century [1]. Electric circuits courses are mostly taught through "*analysis*". Too often, the focus lies on writing and solving sets of simultaneous equations based on Kirchhoff's voltage and current laws (KVL and KCL). In practice, this leads to a circuit methodology that leaves the student facing an unrealistically large number of equations and unknowns, and it results not only in the inability to completely solve the circuit but also in the inability to gain any useful insight into the behavior and purpose of the circuit. The concept of *design-oriented* analysis, as defined by Middlebrook [2], presents a solution to this quandary. Although, Middlebrook promoted the design-oriented analysis approach already in the early nineties, and to a good extent his ideas have successfully taken off in the teaching of microelectronics courses (as attested by the number of excellent textbooks in this field [3-6]), with a few exceptions [7-8], this has not been the case for electric circuits courses. The purpose of this work is to promote the design-oriented analysis methodology to the teaching of circuits, and illustrate its effectiveness through a number of practical examples that have been compiled for dissemination on the web [10]. This work is a qualitative study of how a design-oriented methodology can help improve students' success. In order to validate our thesis we plan to systematically analyze student's grades. Based on our current data, we noticed a 3.37% improvement in the mean student grade over the last two academic years. The data collected is presented in figures 1 and 2. The rest of the paper is organized as follows. Section 2 describes the main motivation and background behind the design-oriented analysis methodology. Section 3 illustrates a few examples of the pedagogical material put together to introduce design-oriented analysis to the teaching of circuits. Finally, Section 4 summarizes our perception about students' response to the teaching methods proposed and provides conclusions.

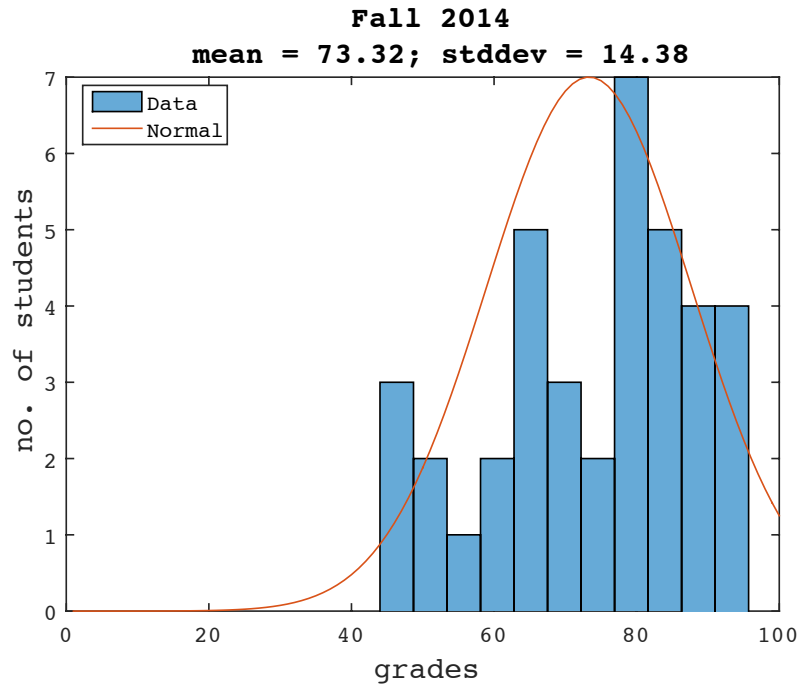


Figure 1. Fall 2014 grade distribution

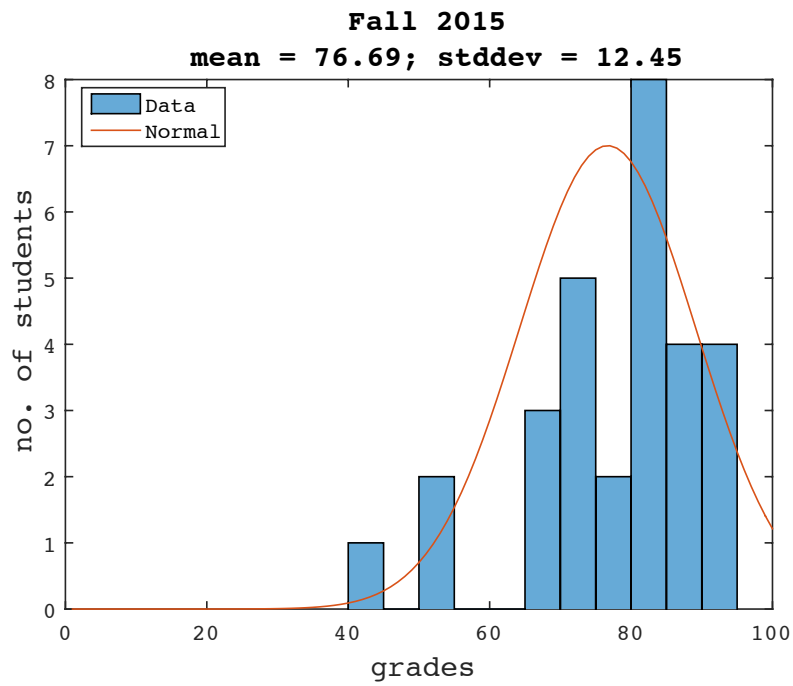


Figure 2. Fall 2015 grade distribution

2. Design-Oriented Analysis: Tenets and Background

Design-Oriented Analysis (DOA) as defined by D. Middlebrook in [12] and [13] follows a completely different teaching paradigm than the conventional attempt of writing KVLs and KCLs until the circuit is modeled with as many equations as the number of unknown voltages and currents we are interested in. As circuit complexity increases, blindly writing KVLs and KCLs becomes extremely inefficient and in most cases prohibitive, so in almost all practical applications the conventional approach becomes a recipe for failure. Unfortunately, the idea that if you do not have as many equations as unknowns you can't solve a problem has been deeply ingrained in most of us from a very early age, so it is extremely difficult to "overcome". In addition, this last misconception is often accompanied by a number of poor habits including: 1) modeling a circuit as accurately as possible and postponing any approximation to the very end, and 2) thinking that the "answer" is acceptable in whatever form it emerges from the algebra.

DOA originates from the realization that design is the reverse of analysis, i.e. the starting point of a design problem (the specification) is the answer to the analysis problem. In practice, this means that the main problem engineers face is that the number of equations is always going to be much smaller than the number of unknowns. As a result the key to DOA is to avoid solving simultaneous equations. Instead, you follow the signal path from input to output and repeatedly simplify the circuit by using Thevenin/Norton reductions and voltage/current dividers. Every time we use a Thevenin's or Norton's transformation we get rid of one loop or one node of the circuit. As a result, by successive use of Thevenin and Norton theorems we can reduce a complicated circuit to a single loop and write the result by inspection. In addition to relying on circuit transformations techniques it is important to realize that we do not necessarily need an exact answer at each step of the process. The exact answer may be too complicated to use. We substitute for the missing equations with inequalities, approximations, assumptions, and tradeoffs. In essence, DOA is a "closed-loop" process that helps to guide and control the algebra so that the result is a "Low-Entropy Expression", where the term "Low-Entropy Expression" is defined as one in which the terms are ordered, or grouped, so that additional insight is obtained into the relative importance of the various contributions to the result. Conversely, "A high-entropy expression" is one obtained by "blind" application of algebraic manipulations and it usually leads to sums of products of circuit elements that give no insight into how the relative values affect the result.

Since the result of DOA is a low-entropy expression, the method allows useful design insight that cannot be obtained by the "dry" numerical answer that would result from the conventional analysis approach. DOA mimics closely the process experienced designers follow. "Real" design is done by a combination of theory, "cut-and-try", "knob-twiddling", and guesswork that eventually grows into competence and intuition. An experienced designer follows a sequence of steps. First, one starts with a simple, approximate model and some basic quantitative expressions that establish the required functionality. Then one gradually augments the model with more details until it reaches the required tradeoff between accuracy and simplicity. As one includes more details the trade-off shifts toward greater accuracy and less simplicity. When a tentative

choice has to be changed, or when simulations or experimental measurements do not agree with predictions, iterations are necessary.

The goal of this work is to promote the design-oriented analysis methodology to the teaching of circuits and to illustrate its effectiveness through a number of carefully crafted application examples. The use of application examples throughout the course is a powerful motivational tool. It helps students see the “big picture” and therefore it ignites their curiosity and ability to put in context the various theoretical concepts they study. The choice of the application examples must be carefully considered. If the description is too long or the result is too abstract, the students miss the connection between the concept and the application. Motivation is key. As noted by Tsividis in [13] there are two crucial differences between today’s students and those of earlier generations:

1. Fewer of today’s students have ever tinkered. “They have no idea where, in practice, the theory fits and why it is needed. In the past, many students had tinkered and could see why the theory they were being taught was useful. This provided motivation, which is missing today” [13].
2. They are seemingly more impatient. “Today’s students are used to immediate gratification. Telling these students that they will see later in the curriculum why circuit theory is useful, does not work” [13].

We do not intend to malign today’s students by invoking Tsividis; however, it is important in the proposed assignments that there is a good balance between freedom and guidance. A too strictly regimented approach suffocates creativity and hinders learning – it is possible for a student to blindly follow instructions and complete an assignment without having really understood much. To avoid this, a certain amount of freedom must be allowed. However, complete freedom is also not appropriate, as many students do not know how to begin to approach the assignment and so they get stuck. Furthermore, it is important to emphasize that active learning experiences are better retained in memory and help make things click – which in turn increase intuition, and motivate further study.

Unfortunately, circuit theory’s textbooks are often written by authors that are not in the field and to make things worse the course is frequently taught by an instructor having little involvement in circuit design. As a consequence students are rarely taught that certain techniques are more frequently used than others and they are given little intuition with respect to the techniques they are asked to learn about. The end result is that to the students all circuits they have seen look the same and it is unclear how they came about and what is their purpose [4]. Emphasis on reality helps reinforce the point that everything the student does is important and useful. Furthermore, it is important to make students realize that one of the essential skills of any experienced circuit designer is the knowledge that any specific circuit topology provides certain desired characteristics and certain shortcomings. It is important to teach students to think about circuit design from a different perspective than the classical approach. To design and analyze circuits effectively it is imperative to gain an intuitive understanding of the various devices and topologies. Without intuitive understanding, the analysis and design of most practical circuits becomes prohibitive. We need students to spend significant effort establishing the mentality and

skills necessary to think about a complex circuit as a “Lego artifact” to be decomposed into a number of differently shaped blocks, i.e. students need to learn how to look at complex circuits from as many different angles as possible so they can “map” complex circuits into simpler topologies. As suggested by Razavi [4], in teaching circuits, instructors must move away from the mindset “Here is a circuit that you may never see again in your life, please analyze it” to “We face the following problem please create a circuit that solves the problem”. DOA constitutes the ideal vehicle to foster the habits and skills required to achieve this shift of mindset. DOA promotes a systematic step-by-step methodology that encourages the creation of a circuit beginning with the simplest topology, identification of its shortcomings followed by continued modification until one arrives at an acceptable solution. Furthermore, while walking through the process, the student is faced both with numerical calculations that provide a feel for the typical values encountered in practice and symbolic calculations that offer insight into the behavior of the circuit, its trends, limits and trade offs.

3. Examples

In this section we present three examples from the course that illustrate how our method deviates from the standard approach taught in circuit design. The examples provided are in increasing order of difficulty, i.e. they require mastering a larger number of circuit theory techniques. The examples are introduced as supplemental material and are made available to the students through the web. Before presenting the specific application examples, the students are guided through a series of tutorials that review the mathematical concepts more frequently used in analyzing and designing electric circuits. The mathematical review is grounded in a context that is relevant to the circuit realm. For example quadratic equations are illustrated in the context of modeling the current-voltage relationship that characterizes the MOS transistor behavior and also as the type of equation [14] that govern the response of many practical electronic systems. To reinforce understanding and motivation, all mathematical concepts reviewed are illustrated through the use of CAD tools. These tools include MATLAB and SPICE (Simulation Program with Integrated Circuits Emphasis). The goal is two fold: 1) we want the students to get familiar with some of the tools more commonly used by today’s practitioners, and 2) we want to encourage and make it easier for them to verify the correctness of their work. The aim is to boost students’ confidence and ignite their ability to look at problems from different perspectives so that eventually they gain the level of insight required for analyzing and designing any complex circuit. Following we present three examples from the course.

Example 1: Wheatstone’s bridge

The Wheatstone’s bridge is used as the front-end circuit in a number of important applications including high precision scales, high precision strain gauge measurements, and biomedical parameter measurements. Despite the advanced applications it is used for, the Wheatstone bridge, is a very simple example for the students to grasp and appreciate even after a very few lectures. A Wheatstone bridge is a circuit for measuring resistances with excellent precision. It consists of a voltage source, four resistors (one of which we want to measure) and an ammeter. The circuit is depicted in Figure 3. The difficulty most students find in analyzing this circuit is the unnecessarily large number of equations derived from the application of KVL and KCL to the three loops in the circuit.

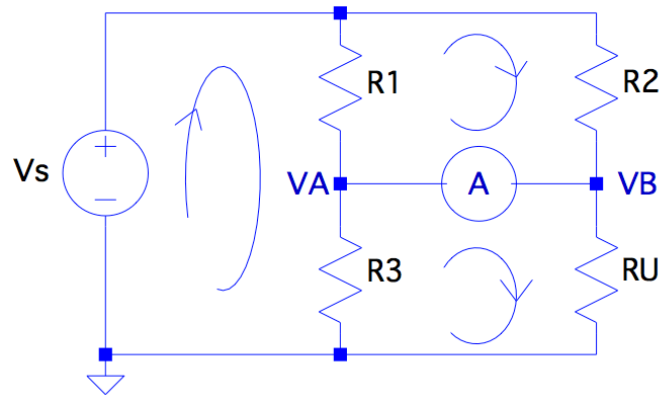


Figure 3. Wheastone Bridge

The key is to look at the circuit from a more intuitive perspective and to focus on the purpose of the structure rather than the specific circuit topology. Since the goal of the circuit is to measure the value of the unknown resistance R_U , the easiest way to approach the problem is by choosing the various circuit elements in such a way that one of the circuit's loops becomes irrelevant. This is equivalent to choosing the known resistance in the circuit in a way that makes the current flowing between nodes A and B equal to zero (that is the same as having $V_A = V_B$). In this way we can “solve” the circuit using the voltage divider rule.

$$\frac{R_3}{R_3 + R_1} = \frac{R_U}{R_U + R_2} \quad \Leftrightarrow \quad R_1 R_U = R_3 R_2$$

Example 2: Switched capacitor circuits

Switched capacitor circuits are often considered an advanced topic and are rarely covered in introductory electrical circuits courses. In reality this class of circuits is extremely useful and find extensive application in most of today's high-performance integrated circuits. It is therefore unfortunate to postpone their treatment. Manufacturing large resistors inside an integrated circuit it not efficient both in terms of the silicon area required and in terms of the precision achievable. Switched capacitor circuits allow us to emulate the behavior of resistors and represent a much more effective alternative both in terms of area and precision. In reality, for students to understand how switched capacitors work all they need is a good intuitive mental grasp of how capacitors behave. An effective model is to think of a capacitor as a “bucket” of charge. In the same way as water is poured in a bucket to be stored for a later use, charge is “poured” into a capacitor. Figure 4 illustrates the analogy between the volume of water in the bucket, the buckets's size (i.e. its cross-section area) and the height of the water in the bucket with electric charge, capacitance and voltage.

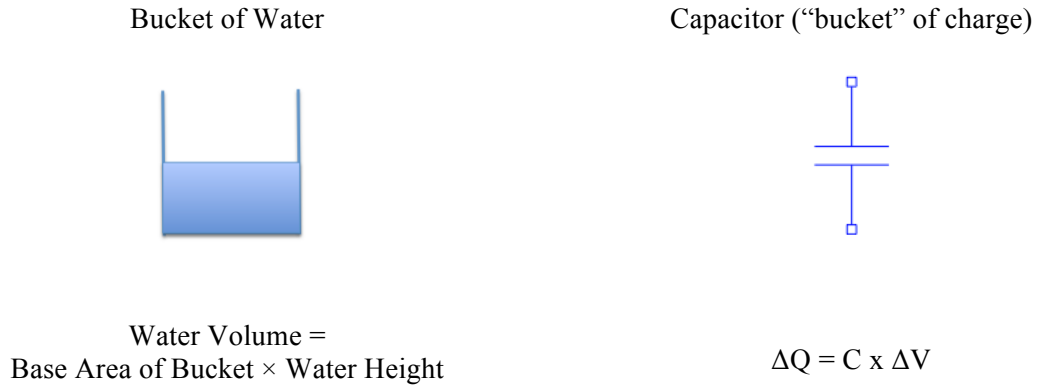


Figure 4. Analogy between bucket of water and capacitor

Since the current flowing through a resistor is given by the ratio of the voltage difference across the resistor and its resistance (Ohm’s Law), the same effective behavior can be achieved using a capacitor by changing the amount of charge (Δq) stored by the capacitor over a given interval of time Δt . In other words the circuits shown in Figure 5 and Figure 6 exhibit the same effective behavior.

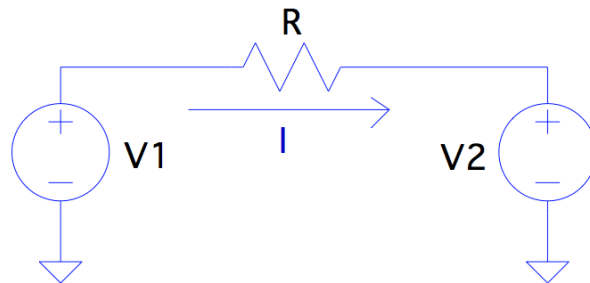


Figure 5. Current flowing through a resistor

$$I = \frac{V_1 - V_2}{R}$$

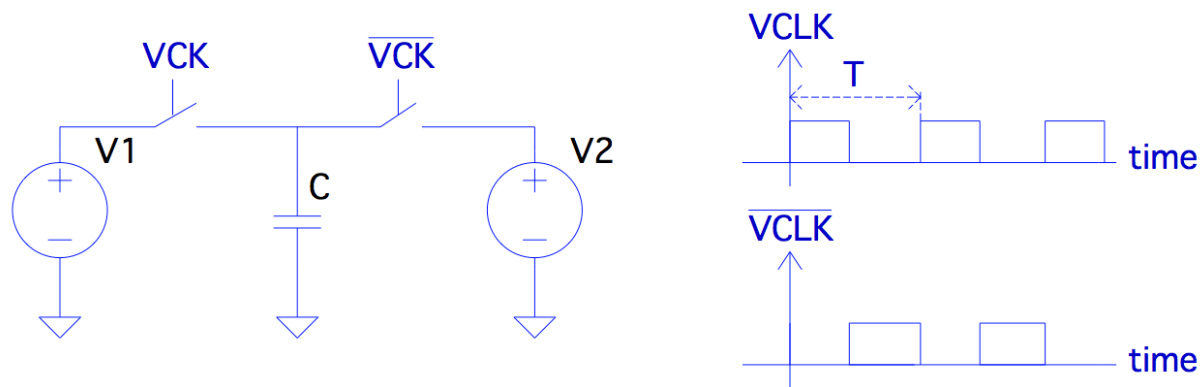


Figure 6. Basic switched capacitor and clock signal V_{CLK} and $\overline{V_{CLK}}$ controlling the switches

When V_{CLK} is high the left switch is ON and the right switch is OFF. The capacitor stores a charge $Q_1 = C \times V_1$. When $\overline{V_{CLK}}$ is high the situation reverses and the left switch is OFF and the right switch is ON. The capacitor stores a charge $Q_2 = C \times V_2$. This means that over the time interval $\Delta t = T$ there has been a charge transfer $\Delta Q = Q_1 - Q_2$ from V_1 to V_2 such that:

$$\Delta Q = C(V_1 - V_2)$$

In other words there is an effective current flowing from V_1 to V_2 equal to:

$$I = \frac{\Delta Q}{\Delta t} = \frac{\Delta Q}{T} = \frac{C}{T}(V_1 - V_2)$$

The net result is that as long as:

$$R = \frac{T}{C} = \frac{1}{C \cdot f}$$

the switched capacitor circuit of Figure 6 exhibits the same effective behavior of the resistive circuit of Figure 5. It is worth noticing that using switched capacitor circuits allows us to achieve large resistances by conveniently modulating the frequency of the clock signals controlling the switches. In practice the two voltage controlled switches in Figure 6 are implemented using MOS transistors.

Example 3: Interconnection between power supply and digital integrated circuits (ICs)

In this example students are expected to model the effect of the wiring between a power supply and the VDD and GND pins of a digital IC. If the length of the wiring between the power supply and the VDD and GND pins of the IC becomes significant the wiring exhibits a non-negligible parasitic inductance. When the digital gates inside the IC switch the amount of current absorbed by the IC varies and the inductive nature of the interconnection causes an undesired fluctuation of the voltage at the VDD pin of the IC. If the VDD fluctuation is excessive the IC may end up malfunctioning. Figure 7 models the interconnection between the power supply and the digital IC. From the perspective of the power supply the digital IC can be modeled as a simple resistive

load. The value of the load depends on the switching activity occurring inside the IC. Figure 8 models the described behavior at the circuit level.

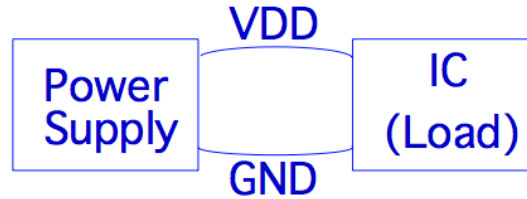


Figure 7. Wiring between power supply and the VDD and GND pins of a digital IC load

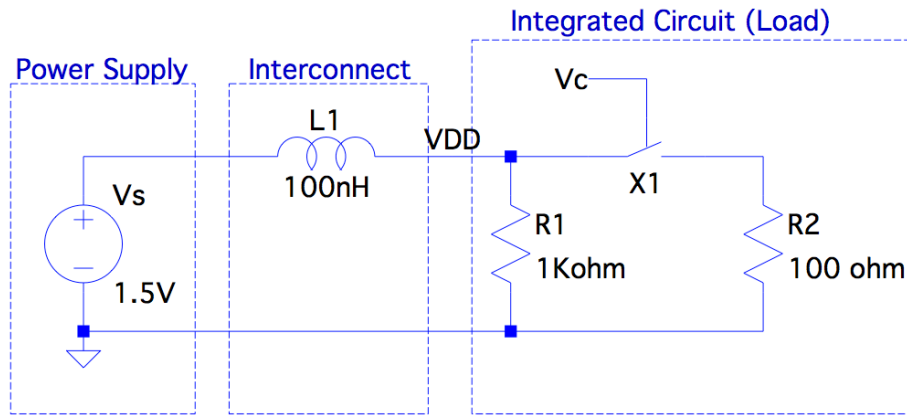


Figure 8. Circuit level model of the interconnection between a power supply VS and a digital IC load.

When the switch X1 is open (that is the activity of the gates inside the IC is low) the voltage VDD at the IC pin settles at $V_s = 1.5V$ and the current absorbed by the IC is equal to $V_s/R_1 = 1.5mA$. The power supply sees the IC as a load of $R_L = R_1 = 1K\Omega$. As soon as the switch X1 closes (that is the activity of the gates inside the IC is high) the IC represents a load of $R_L = R_1 \parallel R_2 \approx 100\Omega$ to the power supply. Since the current through the inductor cannot change instantaneously at the switching instant the current through the inductor remains $V_s/R_1 = 1.5mA$. As a result the voltage VDD drops to $(V_s/R_1)(R_1 \parallel R_2) \approx 0.15V$ which is unacceptably low for the IC to work properly. In order to solve this problem we can connect a capacitor as close as possible to the VDD and GND pins of the IC. For proper operation the voltage VDD must be about $V_s = 1.5$ at all time. When the switch X1 is open in order for VDD to be about V_s the IC must be able to absorb a current of about $I = V_s/(R_1 \parallel R_2) \approx 15 mA$. The current in excess of 1.5 mA must be provided by the capacitor rather than the power supply. Assuming the switching activity is controlled by a clock V_c with period $T = 10ns$ every half clock cycle the capacitor must be able to store (or release) a charge of $\Delta Q \approx I \times T/2 \approx 75pC$. If the IC can reliably operate as long as the voltage fluctuations at the pin VDD are smaller than $\Delta V = 100 mV$ we see that the capacitance C1 must be sized larger than 0.75 nF:

$$C1 = \frac{\Delta Q}{\Delta V} = I \frac{\Delta t}{\Delta V} = 0.75 nF$$

Figure 7 illustrates the use of a decoupling capacitor C1 to help reduce the voltage fluctuation at the VDD pin of an IC.

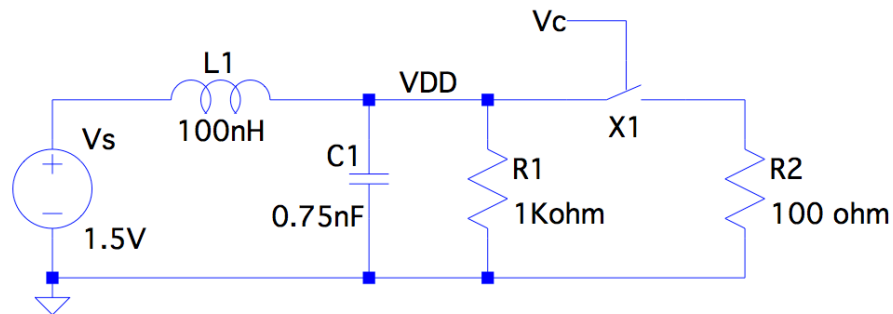


Figure 9. Use of a decoupling capacitor C1 to reduce the voltage fluctuation of the voltage VDD

4. Conclusions and Future Work

The goal of this work is to promote the design-oriented analysis methodology to the teaching of circuits, and illustrate its effectiveness through a number of carefully crafted application examples. The use of application examples throughout the course is a powerful motivational tool. It helps students see the “big picture” and therefore it ignites their curiosity and ability to put in context the various theoretical concepts they study. The entirety of the material developed is compiled for dissemination on a web page for the community at large. So far, the students’ comments, collected anonymously, have been very positive. Here are few of the comments: 1) “This course was very helpful with putting electrical engineering into practical terms. We learned how to design and analyze electronics for practical use and gained intuition for solving complicated circuits. I now know a lot”, 2) “Although it was the hardest class I have ever taken, I still enjoyed it” and 3) “Though it was very confusing and difficult at times, the practical approach was effective in the long run. I learned how to recognize what is important and use observation to simplify problems. All the intuition tips and instructions were helpful. Also, all of the online resources were very helpful for learning and studying for tests”. As we move on with the project, we plan to keep integrating the supplemental material on the web page, and systematically collect data to help in quantifying how the approach impacts students’ success.

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