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# Rationales on a Required Class on Signal and Power Integrity in a Computer Engineering Curriculum

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# Rationale for a Required Course on Signal and Power Integrity in Computer Engineering Curriculum


## Abstract

Two aspects of digital systems are digital logic design and digital circuit implementation. The former is a standard required subject in an electrical and computer engineering curriculum. The latter is usually taught as a senior elective or more often as a graduate class. While the former has become simpler, easier and more abstract, the latter has become more analog, more integrated and a complex system issue especially because of signal and power integrity. A new course has been initiated to introduce signal and power integrity in digital circuit implementation as a fundamental and required course in our computer engineering curriculum. This course will not require electromagnetic fields and waves as prerequisite beyond college physics and therefore will introduce those topics of engineering electromagnetics related to digital circuit implementation. The rest of the course will cover signal and power integrity concepts, models and tools as well as real-world high-speed digital circuit implementations. This paper discusses rationale for this new course as it relates to ever changing high-speed and high density digital system world and engineering practice.


## 1 Introduction

Two aspects of digital systems are digital logic design and digital circuit implementation at chip level or printed circuit board (PCB) level. While the former assumes binary digital signals of logic "1" and "0", the latter must deal with analog nature of physical reality at chip, printed circuit board or chassis levels as speed of digital systems reaches billion cycles per second. While the former has become easier to deal with because of tremendous advancement of computer aided design tools, the latter has become more complex. While the former is a standard and required subject of any electrical or computer engineering curriculum, the latter is often treated as a senior elective or graduate school topic. While the former is pure digital the latter is an integrated part of a system that may have analog and RF circuits as well as sensors and actuators. It is time that digital circuit implementation is considered as a fundamental subject and taught as a required course because it is what digital design engineers must deal with at work.

Digital system implementation has become complex and critical due to a number of implementation choices such as small floor plans, high-speed and mixed-signal design, integration of sensors and actuators and minimum power consumption. One key issue at chip or PCB level implementation is signal and power integrity (SI, PI), which holds the key to success or failure of a digital system implementation. This topic has become so prominent that the phrase "Digital Systems Engineering" has been coined in [1], [2]. Many engineering reference books and a few college textbooks on the subject have been published in the past fifteen years as given in the appendix of this paper. Many technical conferences have special or regular sessions on SI and PI under titles such as high-speed digital designs, power distribution networks, high-speed interconnects, etc.[3] These conferences include DesignCon,, IEEE International Symposium on EMC, IEEE Electronic Components and Technology Conference, IEEE Conference on Electrical Performance of Electronic Packaging and Systems. In addition, Signal Integrity Engineer has become a standard title in large corporations.

It is time to offer a required course on SI and PI in a computer engineering curriculum and furthermore it is also possible to teach SI and PI to computer engineering students without a prerequisite class on engineering electromagnetic fields and waves beyond college physics. The compromise is to add a SI and PI class that covers electromagnetic fields and wave related to SI and PI. The class can focus on presenting relationship between fields, wave and circuits and on how to extract circuit parameters under different working conditions from field or wave models given geometries and material properties of an electronic system. This class will then apply correct circuit models and tools to solve real-world SI or PI problems.

The class may cover the topics such as electric and magnetic field models of lumped-element capacitor and inductor; transverse electromagnetic wave model of a lossless or lossy transmission line; extractions of circuit parameters from geometries of capacitor, inductor and transmission line, high speed behaviors of passive components; frequency spectrum of digital signals; models of drivers and receivers of digital devices, Transmission line impedance discontinuity and termination techniques; coupling mechanisms of electrical and magnetic fields and capacitive and inductive crosstalk; ground noise, Power plane noise and resonance; signal and power integrity issues in high-speed digital systems at printed-circuit board and chip levels.

Computer engineering students will benefit from a class proposed above. The class will serve as a link between real world physical implementation and ideal functional design of an electronic circuit. It will be a podium, probably the only one in a computer engineering curriculum, to combine digital, analog and RF circuits and to traverse between electromagnetic fields and electronic circuits and to relate geometries and material properties to circuit parameters. It will help students to understand differences between high speed and low speed properties of electrical signal transmissions, electrical properties of materials and electronic devices.

We have proposed for this class to be added to the computer engineering curriculum at our school and we will report our experience of this new class after this class has been taught for a couple of years.

## 2 Digital Logic Design and Digital Systems Engineering

Digital system implementation has been called “Digital Systems Engineering” [1] to emphasize its physical nature and system-level aspect. There is a fundamental difference between digital logic design and digital system implementation. Understanding “Digital Systems Engineering” is more a competitive advantage than logic design. One major issue is SI and PI.

### 2.1 Digital logic design and Digital Circuit Implementations

Digital logic design used to assume gates and flip-flops as fundamental components. This is reflected in traditional digital logic design textbooks that start with gates and flip-flops and introduce concepts, models and tools to deal with these components. The assumption is not valid anymore for most digital logic design tasks, which often use register-transfer or behavior level descriptions as fundamental building blocks. New digital logic design textbooks published in the past 10 years have incorporated this trend of higher level abstractions of digital logic systems by making hardware description language a main feature. With better and faster tools for logic designs and high level hardware description languages such as Verilog and VHDL, it has become quite simple and easy to make a logic design of a digital circuit of an average complexity.

The competitive and differential advantage of one digital system design over another is however not at digital logic design level but is dependent on its circuit implementation at chip level, PCB level or chassis level, which has been called "Digital Systems Engineering" [1]. To make a digital system implementation cheaper, faster and more reliable has less to do with digital logic design but everything to do with it physical implementation. There are a number of options to implement a digital logic design: microcontrollers, FPGA chips, semicustom ASICs or full-custom ASICs. Digital system implementation have been made more compact by advancement of system integration technology such as system-on-chip, multiple chip carriers, flip-chip packages, and embedded passives, etc.

## 2.2 Digital Systems Engineering

Digital Systems Engineering is about how to implement digital systems with real-world requirements, which are constrained more and more by small foot prints, mixed signal designs, inexpensive light-weight plastic packages, low power consumption and battery power supply. These issues are hard to understand and require many trade-offs to be considered. In addition, more and more PCB level implementations involve mixed-signal circuits such as analog, digital and RF. This is an area that requires real engineering effort and ingenuity.

The most important commercial product design factor is cost and performance trade-off. Some of the following issues must be considered to make a digital system cost effective.

System level electrical issues must be understood so that they could be modeled for simulation under correct speed and performance conditions. Possible solutions under specific costs must be developed and evaluation to arrive at the best possible design.

Digital systems must be analyzed to find out if they would work reliably. The factors that might cause a system to malfunction include noise budgets, timing budgets, signaling rates, synchronization latency and mean-time to failure, etc.

The last but not the least issue is power distribution and consumption. As speed of digital systems increase, it becomes harder and harder to transmit enough power to the right location of the system at the right time.

## 2.3 Signal Integrity and Power Integrity

Digital Systems Engineering involves transmitting a trapezoidal signal launched at a driver to a receiver with sufficient fidelity or integrity to ensure proper logic switching and signal timing. One of the issues is to make sure high quality of DC power can be delivered to where it is required.

Signal integrity (SI) and power integrity (SI) is about transmitting reliably signal and power in electronic systems such as those built with multiple packages involving printed circuit boards (PCBs) and silicon wafers, multichip carriers, connectors, cables and enclosures. As wireless communications, high speed digital circuits, mixed signal PCBs, hand-held or portable devices and battery power become ubiquitous in more and more electronic devices, understanding SI and

PI has become critical for computer engineers to design reliable and cost-effective electronic products. Topics in SI and PI often involve interaction between electromagnetic fields, wave and electronic circuit. Therefore, knowledge of certain areas of electromagnetic fields and wave is required to understand SI and PI issues.

SI and PI covers real-world interface between ideal digital design and noisy analog reality. It crosses the boundary between electrical design and physical layout. It is also in a general sense to design for manufacturability, reliability and electromagnetic compatibility. Some of the factors need to be considered are data rate and frequency, timing, IC packaging, logic families, printed circuit board routing discontinuities and signal path and path length, PCB materials, specified bit error rate (BER) and cost & time-to-market.

TABLE 1
SOME COLLEGE COURSES ON HIGH-SPEED DIGITAL DESIGN OR DIGITAL SYSTEMS ENGINEERING

| Course Title | Electromagnetic as Prerequisite | Course Number | Level | University |
|---|---|---|---|---|
| Digital Systems Engineering | No | ECE273 | Graduate | Stanford University |
| High-Speed Digital Design | No | CMPE173 | Senior | UC Santa Cruz |
| Signal Integrity for High-Speed Digital Design | Yes<br>El Eng 271 | EE475 | Graduate | Missouri U of Science and Technology |
| High-Speed Digital Design and Signal Integrity | No | 525.434 | Graduate | Johns Hopkins U |
| High Speed Digital Design | Yes<br>ECEN 3400 | ECEN 4224 | Senior Elective | University of Colorado at Boulder |
| High Speed Digital System Design | No | CMPE 265 | | San Jose State University |
| Signal Integrity for High Speed Integrity Circuits | Yes<br>ELCT 361 | ELCT 762 | Graduate | Intel and U of South Carolina |
| Signal Integrity on System bus Technology | No<br>Pre ELCT 762 | ELCT865 | Graduate | Intel and U of South Carolina |
| Digital Systems Engineering | | CSE/ESE 464 | Senior Elective | Washington University in St. Louis |
| High-Speed Digital Circuit Design | Recommended<br>EECS 420 | CSE/ESE 464 | Senior / graduate | The University of Kansas |

## 3 SI and PI Course for Computer Engineering Major

A number of universities offer SI and PI courses as senior elective or graduate courses. Some of them require electromagnetic fields and waves as a prerequisite. Most of them seem to cater to electrical engineering major. It is possible to teach SI and PI to computer engineering students without a prerequisite class on engineering electromagnetic fields and waves beyond university physics. This course must introduce engineering electromagnetic fields and wave related to SI and PI. The course will focus on presenting relationship between fields, wave and circuits and on how to extract circuit parameters under different working conditions from field or wave models given geometries and material properties of a digital circuit implementation. This course will then apply correct circuit models and tools to solve SI or PI problems.

### 3.1 Current State of SI and PI Education at US universities

Table 1 lists SI and PI courses at some universities in the USA. As can be seen from the table, none of the courses is required for an undergraduate degree. The courses are either graduate level or senior elective. 50% of the courses from the table require an engineering electromagnetic course as a prerequisite while the other 50% do not require electromagnetic fields and waves. Some concepts of electromagnetic fields and waves must be understood in order to thoroughly learn issues and solutions for SI and PI. Without relevant electromagnetic knowledge, students would only learn either circuit models as in [1] and [5] or how to apply formulas or follow design guidelines provided by corporations such Intel, TI, et al [6-9]. Clayton Paul proposed to include transmission lines as a required subject in an EE or CPE curriculum and proposed remedies to enhance student's knowledge on the required mathematical skills [4].

### 3.2 A survey from a group of EMC and SI engineers and managers

Most computer engineering curricula in the USA do not have required classes on electromagnetic fields and wave beyond physics. Computer engineering curricula are often too crowded to add a required electromagnetic class for one semester or two quarters. Students often feel electromagnetic classes are irrelevant to their career as they don't see how the classes relate to their future career in computer engineering. Would it be possible to introduce SI and PI without requiring a comprehensive class on electromagnetic fields and waves? Would it be beneficial to computer engineering major to take a SI and PI class without a comprehensive engineering course on electromagnetic fields and waves? Clayton Paul suggested some ideas in [4] to add transmission lines and related mathematical skills to computer engineering. A SI and PI course that covers these mathematical skills and transmission lines would be another alternative solution.

We conducted a survey to ask a number of questions related to a class on SI and PI for computer engineering major at an industrial consortium on EMC and SI that has attendees from major electronic companies in the USA and other countries. The attendees of the consortium are experienced EMC and/or SI engineers or engineering managers. Nine people filled the survey forms. We posed three questions as follows. (1) What is the current status of SI and PI education? (2) Is a required undergraduate SI course needed for computer engineering major? (3) What topics should be covered in such a SI course?

The results of this survey have indicated our original understanding that there is a need for a SI and PI course for computer engineering major and our planned course covers majority of the topics that are important to the people who answered the survey questions.

We stated the purpose of our survey as follows. "We welcome your comments and ideas regarding the necessity of offering a required undergraduate course on signal and power integrity to undergraduate computer engineering students. Most computer engineering curricula in the United States do not include a course on either electromagnetics or signal and power integrity. We plan to offer a course covering electromagnetic fundamentals and signal integrity in digital systems for computer engineering students at the junior level. We ask for your help in defining such a course so that it might meet the needs of industry."

| What is the current status? | Excellent | Good | Average | Poor |
|---|---|---|---|---|
| How do you feel about current undergraduate engineering education in signal integrity and high speed digital systems? | | 2 | 3 | 4 |
| Do computer engineering graduates have sufficient knowledge of signal and power integrity? | | | 4 | 5 |
| Do computer engineering graduates have an adequate understanding of the fundamentals of EM fields and waves? | | | 6 | 3 |

| Is a required undergraduate SI course needed? | Absolutely | Yes | Neutral | No |
|---|---|---|---|---|
| Is offering a required signal integrity course to computer engineering undergraduates a good idea? | 5 | 4 | | |
| Would you value entry level computer engineers who have taken such a course? | 5 | 4 | | |
| Would such knowledge offer computer engineering graduates a competitive advantage? | 6 | 3 | | |
| Is this course of sufficient importance that it should replace another required course in the CPE core curriculum? | 1 | 4 | 4 | |

| What topics should be covered in such a SI course? | Vital | Important | Neutral | Least important |
|---|---|---|---|---|
| EM fundamentals | 4 | 4 | 1 | |
| Electrical and magnetic flux and field structure | 6 | 2 | 1 | |
| Material properties – loss and dispersion | 4 | 5 | | |
| High-speed behavior of passive components | 2 | 7 | | |
| Wave propagation and reflection | 5 | 4 | | |
| Transmission lines – time domain analysis | 6 | 3 | | |
| Transmission lines – frequency domain analysis | 5 | 4 | | |
| Matching and termination | 4 | 5 | | |
| S-parameters | 6 | 3 | | |
| Time-domain reflectometry | 1 | 5 | 2 | |
| Physics-based model extraction | 2 | 3 | 4 | |
| IBIS models and SPICE | 1 | 5 | 2 | |
| High-speed PCB routing and layout | | 5 | 4 | |
| Signal referencing and power distribution | 2 | 7 | | |
| Laboratory and measurement | 5 | 4 | | |
| Simulation and modeling | 3 | 5 | 1 | |

## 4 A New Required Course on SI and PI for Computer Engineering Major

A new required course on SI and PI has been proposed and approved at one of the schools of the authors for computer engineering major. The course will be one quarter and 4 credit class and will have three 50-minute lectures and one 150-minute lab period per week for ten weeks.

The catalog description of this course is given in Table 2 and its objectives are listed in Table 3. The proposed textbook is Advanced Signal Integrity for High-Speed Digital Designs by Stephen Hall and Howard Heck [10]. Another possible textbook for this course is Digital Signal Integrity by Brian Young [11].

The course will discuss thoroughly capacitors, inductors and transmission lines from both points of views of fields and waves, and circuits and it will also emphasize field and wave properties of capacitors, inductors and transmission lines as they are related to component geometry, electrical and magnetic material properties and speed of signal transmission. It will discuss constraints under which field and wave models can be simplified to valid circuit models. The rest of the course will focus as much as possible on circuit models of these passive components and their relation to signal and power integrity so that computer engineering students will not feel overwhelmed with fields and waves. The course will also introduce advanced modeling and simulation tools and high-speed design and implementation techniques.

TABLE 2

CATALOG DESCRIPTION OF HIGH SPEED DIGITAL DESIGN COURSE

| |
|---|
| Signal path modeling through connecting lengths of transmission lines with lumped element models of discontinuities. Circuit parameters from geometries and material properties for resistance, capacitance, inductance and transmission line segments. Lossless and lossy transmission lines circuit modeling. High-frequency and high-speed behavior of passive components. Frequency spectrum of digital signals. Digital device driver and receiver modeling. Transmission line impedance discontinuity and termination techniques. Electric and magnetic field coupling mechanisms for capacitive and inductive crosstalk. Ground noise, power plane noise and resonance. Signal and power integrity issues in high-speed digital systems at both the printed-circuit board and chip levels. |

Table 3 presents basic objectives of this course to cover theoretical and practical aspects of SI and PI as well as modern tools for SI and PI analysis and design. Software tools for printed circuit board design and analysis will be introduced. Measurement instruments will also be introduced such as vector network analyzer and digitizing oscilloscope for time-domain reflectrometry.

## 5 Discussions

This paper has presented rationale for a new required course on signal and power integrity for digital circuit implementations for computer engineering major. The course would bridge the gap between extensive coverage of digital logic design as a required undergraduate subject and digital systems engineering that is sparsely covered in an undergraduate curriculum. The course will introduce electromagnetic fields and waves from engineering point of view and will focus on high-speed circuit models as much as possible. After taking this course, a student will be able to understand and appreciate high-speed effects of digital circuits and signal transmission and to know how to choose right circuit models for passive components such as capacitors, inductors, connectors and transmission lines. This course has been approved to be offered at the university of some authors of this paper. The effectiveness on the competiveness of students after taking this course and lessons of professors from teaching this course will be presented in the future as more experience is gained on this new endeavor.

TABLE 3
OBJECTIVES OF HIGH SPEED DIGITAL DESIGN COURSE

1. Analytically describe and characterize the electrostatic models for parallel-plate and coaxial capacitors and the magnetostatic model for a coaxial inductor.
2. Understand how electrical and magnetic field structures depend on geometry and material properties and qualitatively predict capacitance and inductance from geometry and material properties.
3. Describe the physical mechanism involved in electromagnetic wave propagation and how material properties can lead to dispersion and loss.
4. Understand EM field foundations of the telegrapher equations analytically describe and characterize wave propagation within the telegrapher equation environment in regard to propagation and reflection.
5. Understand electrical length and how, in principle, lumped element models may be extracted from common signal path discontinuities such as connections and vias using time- and frequency-domain simulation and measurement.
6. Analyze digital signal propagation through a transmission line with resistive, capacitive and/or inductive loads by bounce diagram, simulation and measurement. Identify possible impedance mismatch on a transmission line and find suitable termination techniques such as series, parallel, Thevenin, RC, and controlled- impedance terminations.
7. Identify coupling mechanisms such as those of electric field (capacitive), magnetic field (inductive), common impedance and understand the impact of geometry and material properties on coupling.
8. Understand high-frequency behavior of passive components and characterize their high-speed behavior through measurement.
9. Identify fundamental frequency and harmonics of a trapezoidal pulse train and its Bode plot.
10. Obtain linear models of digital signal driver or receiver from data sheet and demonstrate knowledge and application of I/O Buffer Interface Specification (IBIS) model.
11. Find worst-case maximum clock speed of a clock-synchronous circuit, given clock skew, clock jitter, setup and hold times, propagation delays and timing margin.
12. Identify sources of crosstalk and analyze impact of crosstalk on a circuit.
13. Understand high-speed power plane noise issues and selection criteria for bypass capacitors.

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## Appendix: Selected Engineering Reference Books or Textbooks on SI and PI


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