A context for unstructured experimentation: What resources are available to the student tinkerer?

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"What I hear, I forget;
What I see, I remember;
What I do, I understand."

– Old Chinese proverb

Abstract: Education for the digital generation can be thought of as a process of classroom and laboratory learning in which fundamental principles and analytic techniques are presented to students. A common feedback theme from graduates is that they had to learn "the real stuff" after graduation or on a co-op job. We hypothesize that unstructured experimentation – tinkering - by students totally outside the academic schedule would improve abilities to relate classroom topics to application. This is a review of what resources are available for students, defined as people with limited time and limited money, which would allow them to experiment in ways that could provide significant educational value. A set of development boards, software tools, and test equipment is presented that are available for students.

A common complaint from engineering graduates, echoed by many employers, is that they had to learn "the real stuff" on the job; that the theory and analysis taught in class and labs didn't really make sense to them until they could apply it. Schools are sympathetic to the need to incorporate more practice into their teaching but are faced with the need to provide a well grounded treatment of engineering basics. It would be difficult to alter the engineering curriculum to include "the real stuff" without sacrificing the theoretical depth and breadth that students will need; there is only so much time available for classes, labs, study time and homework preparation.

Dale (1969) has summarized the ability of students to recall material for various means of presentation (see Table 1). His summary indicates that a participatory style of presentation has substantially better recall than others, particularly the common classroom lecture. This example reinforces the anecdotal feedback from new graduates about their need to learn on the job in order for their education to make sense to them.

Table 1
Recall ability for different types of presentation

Type of Presentation	Ability to Recall	
	after 3 hours	after 3 days
Verbal (one-way) lecture	25%	10-20%
Written (reading)	72%	10%
Visual and verbal (illustrated lecture)	80%	65%
Participatory (role plays, case studies, practice)	90%	70%

Adapted from: (Dale, 1969).

The constructivist theory of knowledge is one that sees knowledge as being assembled through experience as opposed to being transferred from one person to another (Domin, 1999). That theory would lead us to believe that learning takes place whenever experimentation and practice are undertaken. Our hypothesis is that students who have the opportunity to experiment on their own time will be better able to assimilate their classroom subjects. This work explores one basic requirement of the hypothesis: are there sufficient resources available to students to allow them to pursue a range of experimentation at reasonable cost and with reasonable initial learning curves outside the support of the university?

A simple taxonomy will be used to evaluate what technical resources students could take advantage of for their own unstructured experimentation. A somewhat arbitrary limit of $100 is imposed for everything except test equipment. Individual, as opposed to group or department purchases, are assumed.

The taxonomy we use is as follows:

a. Analog hardware (Table 2)
b. Digital hardware (Table 3)
c. Mixed signal hardware (Table 4)
d. Language compilers and software development environments (Table 5)
e. Test equipment (Table 6)
f. Breadboard and prototyping resources (Table 7)
g. Communities and publishers (Table 8)

We have assembled a collection of resources in each category of the taxonomy that shows that it is feasible for a student with limited resources to experiment on his or her own. It is possible for students to assemble enough resources for whatever interests them using the references below. We can only imagine what might happen if the bookstores in engineering schools were to stock some of these things.

The remainder of this paper will be a summary of typical resources.

For analog design, the primary experimental requirement is the ability to simulate a circuit design. After that, some way of creating a circuit board is needed. Several excellent programs allow users to create and simulate analog, digital, or mixed circuits. Table 2 lists a variety of such resources. Table 6 has a list of inexpensive test equipment and Table 7 has sources of components such as transistors, integrated circuits, passive components, wire and cable, and a wide variety of other parts and resources.

Table 2

Analog design resources including circuit simulation software, schematic capture, and board layout software.

Description	Source	URL	Cost
Micro-Cap circuit simulation software	Spectrum Software, Inc.	http://www.spectrum-soft.com/index.shtm	Free version available, limited number of nodes
Cadence/ORCAD PSpice software plus schematic capture	Cadence, Inc.	http://www.cadence.com/products/orcad/pages/downloads.aspx	Limited demo version free download
Schematic capture and board layout	ExpressPCB, Inc.	http://www.expresspcb.com	Free but proprietary, only can be used to order boards from vendor
Schematic capture and board layout	Cadsoft	http://www.cadsoftusa.com/	Free, generates standard output files useable by any board vendor
Design tools, PLL, active filter, SMPS	National Semiconductor	http://webench.national.com	Free, links to National parts

Digital design is well supported by major component vendors. It is possible to design a reasonably complex sequential circuit, simulate it, and program a device using free software and very reasonably priced development boards. The resources available to students for free or low cost are not sophisticated enough to create state-of-the-art microprocessor designs, but they will get people a long way down the road to understanding the stuff. Table 3 shows a representative sample of design and experimentation resources.

Table 3
Digital Hardware, including FPGA, microcontroller and microprocessor development resources and components.

Description	Source	URL	Cost
Micro-Cap circuit simulation software	Spectrum Software, Inc.	http://www.spectrum-soft.com/index.shtm	Free version available
Xilinx FPGA design software	Xilinx, Inc.	http://www.xilinx.com	WebPack software is free
Altera FPGA design software	Altera, Inc	https://www.altera.com/support/software/download/sof-download_center.html	Quartus II Web edition is free
FPGA development board, Xilinx	Digilent, Inc.	http://www.digilentinc.com	Basys 2 FPGA board with 100k gate Spartan-3E is $59, academic price
Microcontroller development board, Microchip	Digilent, Inc	http://www.digilentinc.com	Cerebot 32MX4 with PIC32 processor, $59
Microcontroller development board, Atmel	Digilent, Inc	http://www.digilentinc.com	Cerebot Nano with Atmega168, $19.95
Arduino, an open source hardware platform based on Atmel microcontrollers	Various, including Sparkfun, Adafruit, and Modern Device Company	http://www.moderndevice.com http://www.sparkfun.com http://www.adafruit.com	Varies depending on board and kit/assembled. From $12.50 to ~$50, most around ~$25
Wiring	Various	http://www.sparkfun.com	$89 from Sparkfun. IDE is free.

Mixed signal design are very important in many areas of industry today. The means to experiment with analog and digital circuits in one platform is more limited than are the purely digital, but there are several excellent packages available. The learning curve is more challenging with these platforms since each vendor has its own architecture and development environment. The investment in learning a platform will tend to tie the experimenter to that vendor's products until such time as a significant capability cannot be found in them. Table 4 has two of the available platforms and a very intriguing opportunity to explore software defined radios.

Table 4

Mixed signal hardware, including software development tools and hardware boards

Description	Source	URL	Cost
Cypress PSOC starter kit	Cypress Semiconductor	http://www.cypress.com/?rID=38235	$49, a basic development board with software.
AC164120 – Signal Analysis PICtail(TM) Daughter Board	Microchip	http://www.microchipdirect.com/ProductDetails.aspx?Catalog=BuyMicrochip&Category=General%20Purpose&mid=1&treeid=6&lmid=604	$25 works with PicKit 1 Flash Starter Kit, $36. Allows analog signal recording and analysis, FFT, etc.
Softrock II software defined radios	Tony Parks, KB9YIG	http://www.kb9yig.com	$20-60 for receiver, transceiver, and amplifier kits. Works with sound card and free software to make a full software-defined radio

For software experimentation, a minimum of a compiler is required. To do more than simple programs, some sort of debugging environment is necessary. The open source movement has created several excellent tools to do just that. Table 5 has a brief list.

The Arduino project is worth particular mention since it combines a variety of very inexpensive hardware platforms with a software environment that is exceptionally easy to use. It is also straightforward to develop software of significant complexity and program it into the platforms.

Table 5

Language compilers and software development environments

Description	Source	URL	Cost
C/C++ compiler for PIC 24 parts	SourceBoost Technologies	http://www.sourceboost.com/Products/BoostCpp/BuyLicense.html	$99 non-commercial use license
GNU C/C++/JAVA compiler	Gnu.org	http://www.gnu.org	Free compilers available for a wide variety of architectures including AVR, ARM, and Windows
Python	Python.org	http://www.python.org/download/	Free, runs on Windows and variants of UNIX

Wiring	Wiring.org.co	http://wiring.org.co/	Free, software development environment intended for electronic arts and learning programming. Runs on Wiring programming platform, $89 from Sparkfun
Arduino IDE	Arduino.cc	http://arduino.cc	Free, a variant of C with extensive library support to make programming an Arduino board very simple

Experimentation doesn't get very far without some sort of test equipment, ranging from simple meters to logic analyzers. Professional test equipment is priced well out of range of the student experimenter. Fortunately, there are alternatives. Table 6 lists a number of inexpensive, limited, instruments that are readily available.

Table 6

Test equipment. Mostly audio frequency to the low number of Megahertz.

Description	Source	URL	Cost
Oscilloscope	Sparkfun	http://www.sparkfun.com/commerce/product_info.php?products_id=9625	$99, miniature (very) audio frequency scope, 1Msps
Frequency counter	Sparkfun	http://www.sparkfun.com/commerce/product_info.php?products_id=9003	$34.95, audio frequency counter kit, assembly required
Function generator	Sparkfun	http://www.sparkfun.com/commerce/product_info.php?products_id=9002	$34.95, audio frequency function generator kit, assembly required
Oscilloscope, logic analyzer, spectrum analyzer, recorder, and logic generator	Hobbylab	http://www.hobbylab.us/	$169.50, audio frequency test box, dual channel, assembled
IOBoard	Rensselaer Polytechnic Institute	http://mobilestudio.rpi.edu/Project.aspx	Price available from RPI. ~$150. This project includes a variety of boards produced principally for

			RPI but available by special order. It includes a free software package that allows use of the board as an oscilloscope, logic analyzer, FFT spectrum analyzer, …

The experimenter working with any kind of hardware will require at least components and possibly circuit boards. There are a number of excellent vendors who will handle small quantity orders, see Table 7.

Table 7
Breadboard and prototyping resources

Description	Source	URL	Comments
Components	Digi-Key	http://www.digikey.com	Huge selection of parts and subassemblies
Components	Mouser	http://www.mouser.com	Huge selection of parts and subassemblies
Components	Avnet	http://www.avnet.com	Lots of development kits, not as many parts
Circuit boards	Beta Layout	http://www.pcb-pool.com	$41 for 16 sq. in. board, 8 day delivery. Takes most design format layout files including Eagle and Gerber
Circuit boards	AP Circuits	http://www.apcircuits.com	$47 for 16 sq. in. board, rapid delivery, $28 delivery cost.
Surplus electronics	All Electronics	http://www.allelectronics.com	Surplus and opportunistic purchase electronics. Good source of basic components in small quantities. Excellent service.

Finally, it is worth including sources for reference materials and informal education. Table 8 shows a variety of resources for the student who wants to find inspiration.

Table 8

Publishers and on-line communities of experimenters and practicitioners.

Resource	Description	URL	Comments
American Radio Relay League	The national association of amateur radio	http://www.arrl.org	Publishers of a wide variety of technical subjects, mostly related to radio practice. See especially QEX, a bimonthly magazine devoted to experimentation
Circuit Cellar	The magazine for computer applications	http://www.circuitcellar.com	Monthly magazine devoted to computer experimentation.
Make	Magazine and web site for experimenters	http://www.makezine.com	Magazine and web site focused on people who like to make their own toys, ranging from very simple to very complex. Lots of technology.
Society of Amateur Radio Astronomers	Web site for radio astronomy	http://radio-astronomy.org	Web site for an organization for people interested in radio astronomy that can be practiced by the backyard experimenter (no big dishes)

References

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