Introduction

Increasingly, consumer electronics is the driving force behind technological advance, whereas in the past it was military and space projects. Consumer electronics has become the leading edge of technology because of the potentially huge sales volumes. The market is extremely competitive and so big global companies invest in a huge research and development effort in order to introduce new products with better features and performance than their rivals. The study of consumer electronics, therefore, has the double benefit that it is about state-of-the-art technology as well as being interesting and relevant to our everyday lives. However, simply to study the current product range's features and standards would hardly be a suitable subject for academic study, and also the subject changes so fast that everything would be out of date too quickly. A compromise has to be drawn therefore between describing the interesting features on the one hand, and explaining the underlying principles on the other.

This module is primarily aimed at students of industrial design, product design or general engineering that require some understanding of how electronic systems work and what they are capable of. In fact, electronics is so all-pervasive in modern life that there are few students that would not benefit from an elementary understanding of the subject – business, medicine, aviation, communications, transport, space exploration, industrial automation, crime prevention, science, entertainment, music, gaming and environmental monitoring have all been revolutionised by electronics. This module should also be valuable for electronic and electrical engineering students in the early years of study, because courses often bombard the student with theory and fail to convey the "big picture".

The primary aims of this module are, therefore, to:-

1. Give an understanding of the design and manufacture of consumer electronic products
2. Demonstrate the complexity of many everyday items from systems design aspects to semiconductor device technology
3. Introduce microcontroller programming techniques and give an introduction to the design and integration of embedded systems in modern products.
4. Demonstrate the importance of the fundamentals of Physics in a range of technology areas
5. Give a practical context to some of the most advanced subjects in Engineering, such as communications theory and signal processing, control theory, electromagnetism and semiconductor physics.

In studying electronics it is all too easy to get bogged down with details like resistor colour codes and different types of capacitor. If there was just one single motivation for writing these notes, it is to show that electronics is a fascinating subject. It is one of humankind's greatest inventions and we have only just started to exploit its full capabilities. Product designers are particularly lucky that they do not have to worry about technical details of electronic design, but can instead concentrate on the shape, form, function and style of the product. However, armed with the broad coverage of electronics given in this module, product designers will be far better equipped to innovate and design products to suit user needs in the future.

The underlying physical and mathematical principles that are relied upon in some of the sections include:-

Wavelength; frequency spectrum
Semiconductors
Interference, standing waves, diffraction
Total internal reflection
Digital signals, analogue-digital conversion
Feedback and control
Fourier series; time and frequency domain representations of signals

However, fear not because these are treated at a very descriptive level. They cannot be avoided though; the mathematics of Fourier series is essential in understanding the nature of distortion in a Hi-Fi system or how digital TV works. And some knowledge of wave propagation is essential for understanding why wireless networks use certain frequencies whilst satellite TV uses others.

1 Moore's Law and system-on-chip

It is well known that in the business of consumer electronics, customers generally get (and, indeed, expect) MORE FEATURES for LESS MONEY as technology advances. The key to this is the continual and rapid development of silicon technology, allowing more and more transistors to be incorporated on a single chip. Gordon Moore, a co-founder of Intel, predicted in 1965 that the number of transistors on a chip could double every year. This famous prediction has developed into Moore's Law, which is an empirical law that accurately charts technological progress in the microelectronics industry. Figure 1 shows a graph from Intel that charts this evolution of technology. However, it should be emphasised that this is plotted on a logarithmic scale, which tends to underplay this dramatic development of computer technology. Re-plotting the data in Figure 2 on a linear scale shows, convincingly, that we only recently entered the information age. By putting more transistors onto a single chip, clearly a given product will require less chips and less associated components on a circuit board. This, allied with the globalisation of the electronics manufacturing business, as illustrated in Figure 3, is why consumers have become accustomed to cheaper and better products every year.

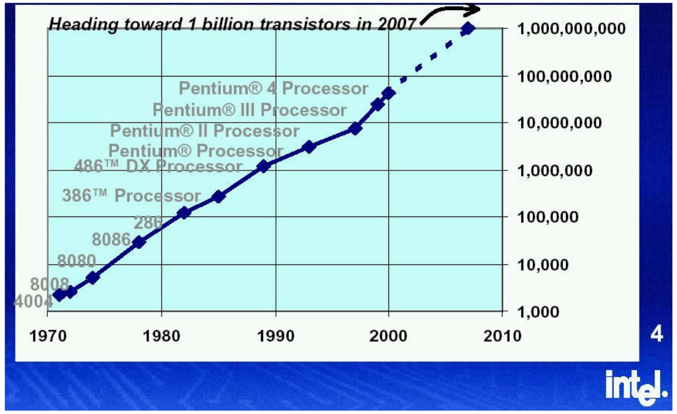


Figure 1 An Intel graph of processor complexity vs. year, illustrating Moore's Law. Copyright Intel Corp. The milestone of 2 billion transistors was reached in 2008.

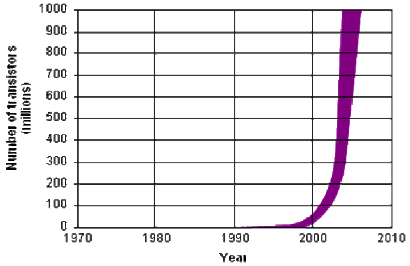


Figure 2 Intel's same numbers on a linear scale

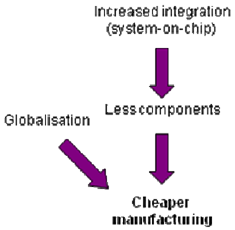


Figure 3 Diagrammatic representation of how consumer electronics has become so affordable

2 A brief timeline of consumer electronics

"We only recently entered the information age" is a bold claim that requires substantiation. A worthy method of investigating the claim is to briefly study the history of consumer electronics and develop a timeline of how the main audio, video and communications products have developed. Figure 4 shows a simplified timeline of some of the most important developments in communications, radio and television. The telephone came first, around 1876, followed by the Gramophone in 1887. Audio recording had been demonstrated before, most notably by Thomas Edison with his cylinder-based Phonograph, but it was in 1887 that Emile Berliner patented the disc-based machine (the Gramophone) that is similar to what we know today. Broadcasting has its roots in Marconi's successful demonstration of radio communications across the Atlantic in 1901. Radio broadcasting became established in the 1920s and TV started appearing shortly after John Logie Baird's demonstration of an electromechanical television in 1926. It was American inventor Philo Taylor Farnsworth who invented the electronic scanning system familiar today a couple of years later. He was awarded a string of patents, which he later sold to RCA, which became a giant in the world of TV and radio. The RCA name is now owned by Thomson (France). The 50's, 60's and 70's saw extensive development of colour television and recording and the first portable audio products.

The mobile telephone has its origins in Motorola's radiotelephone of 1946. It was not until 1983 that the world's first cellular phone was introduced by Motorola, and in 1991 GSM phones were introduced – a digital system with greatly enhanced speech quality. Although personal computers were available about a decade before, GSM phones were one of the first consumer products that used digital electronics to perform real-time processing of signals. The 1990s can therefore be considered (debatably) the start of the digital consumer product revolution, with the DVD player (1996) and portable MP3 player (1998) appearing in the same decade. In the short time since, companies have developed multifunction handheld devices with cellular and internet connectivity, voice-directed navigation, games, and audio and video playback.

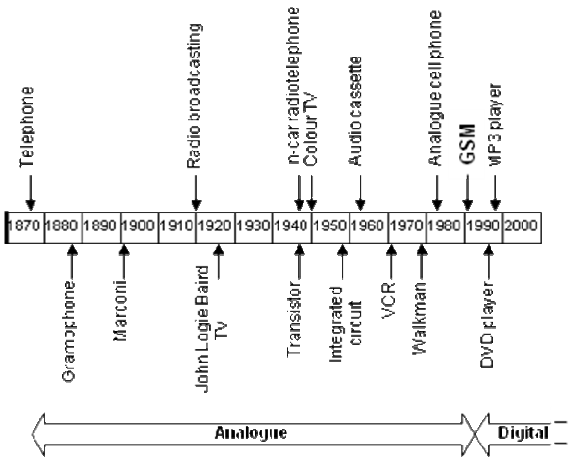


Figure 4 A simplified timeline of developments in consumer electronics

3 Dimensions of electronic devices

The kind of electronics usually encountered in school or college will typically use breadboards for prototyping and students will plug in transistors, resistors, capacitors and maybe simple integrated circuits. Typical projects such as flashing LED circuits and crystal radios may be highly educational but don't always create enough enthusiasm for students to aspire to a career in electronic engineering. In recent years, learning electronics has become much more fun thanks to the advent of the microcontroller and a host of hands-on robotics experiments.

Still, however, working with microcontrollers on prototyping boards fails to convey just how amazing modern electronics has become. Modern processor chips can have more than one Billion transistors, each with dimensions smaller than 50nm. For those not familiar with the letter prefixes for SI units, "nm" stands for "nanometres". Table 1 lists the most common prefixes, from ***T*** for "Tera" (a million million…) to ***a*** for Atto (a millionth of a millionth of a millionth…). To show just how remarkable a modern transistor is, Figure 5 compares its size with the dimensions of various common things.

For another way to gain an appreciation of just how complicated a modern silicon chip is, imagine the components on the chip were scaled up to the size of some everyday object: If the transistors were houses and the tracks connecting them together were roads, a state-of-the-art microprocessor would be more complex than the whole of the US built environment of cities, roads and towns!

Table 1 Commonly-used prefixes for SI units

10^{12}	1000000000000	Tera	T
10^{9}	1000000000	Giga	G
10^{6}	1000000	Mega	M
10^{3} (1000)	1000	Kilo	k (lower case)
10^{0} (i.e. 1)	1		
10^{-2}	0.01	centi	c
10^{-3} (0.001)	0.001	milli	m
10^{-6}	0.000001	micro	µ
10^{-9}	0.000000001	nano	n
10^{-12}	0.000000000001	pico	p
10^{-15}	0.000000000000001	femto	f
10^{-18}	0.000000000000000001	atto	a

There is a full set at http://physics.nist.gov/cuu/Units/prefixes.html

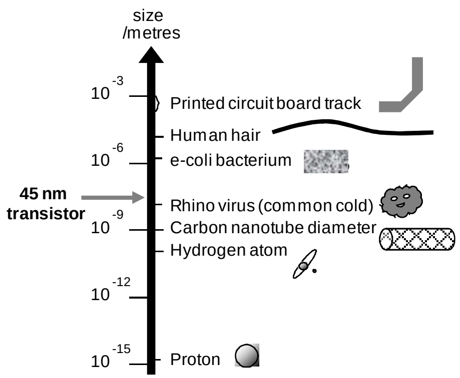


Figure 5 A comparison of the dimensions of various common things (logarithmic scale)

4 The electromagnetic spectrum

Electromagnetic waves are vital to almost all communications systems and modern consumer products. Radio waves, infrared, visible light, UV radiation and X-rays are all forms of the same phenomenon of electromagnetic wave propagation. Some of the most important frequency bands and applications of the electromagnetic spectrum are shown in Figure 6. This is, once again, on a logarithmic scale: X-rays have a frequency around a billion times the frequency of a mobile phone radio signal. Of course, not all these frequencies can be generated easily (if at all) by conventional transistor-based electronics. High power microwaves, for example, are generated in a *magnetron* for cooking. Light, for optical storage and communications, is generated by a *laser*.

Wavelength (λ) is inversely proportional to frequency; assuming free space propagation the relationship $c=f\lambda$ can be used where c is the speed of light in vacuo. The speed of light, c, is one of the most important physical constants in the Universe and is exactly 299,792,458 meters per second. This exactness has been achieved by modifying slightly the definition of other SI units, such as the metre.

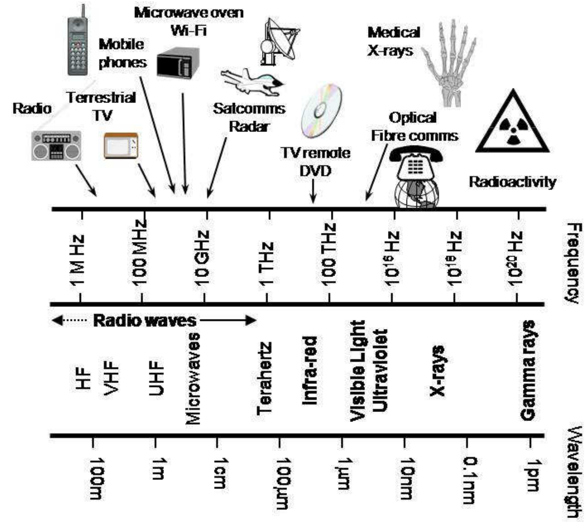


Figure 6 Frequency, wavelength and terminology for various applications of electromagnetic waves

5 The multidisciplinary nature of electronic product design

As mentioned earlier, a state-of-the-art integrated circuit is more complex than the whole US road network. It is not difficult to justify the claim, therefore, that electronic engineering is one of the most challenging careers of all. In this subject, it is necessary to cope with exceptionally rapid technological change. It is taken for granted that electronic engineers also have computer skills, scientific analysis, maths, practical skills, common-sense, and some artistic tendencies. It will become evident throughout this module that modern electronic products, such as cellular mobile handsets, are extremely complex. As a result, teams of people are required at all levels of design. It will also become clear that, in many cases, products from competing manufacturers may have essentially the same electronics inside. The iconic iPod™ serves to illustrate the new phenomenon that, notwithstanding the need for high technology electronic circuits, it is often the skill and flair of the product designers that make the difference between a product succeeding or failing in the marketplace. The iPod™ was perhaps one of the first of a new generation of products that consumers felt they *had* to own, simply because it looked so cool.

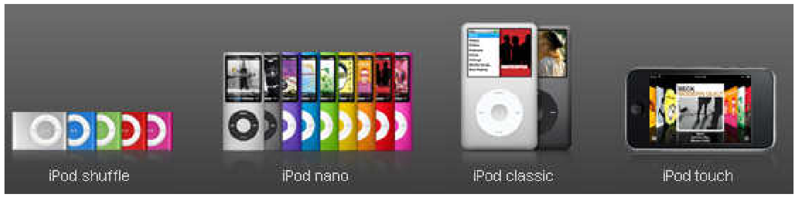


Figure 7 The 2008 iPod™ family © Apple Computer Inc

5.1 The knowledge pyramid

Developing this idea of a multidisciplinary team further, consider the different aspects involved in the design of an MP3 player, from the integrated circuits themselves through to the finished product:-

Semiconductor physics: Solid state MP3 players would not be sought-after products if they could not store huge libraries of music. Advanced semiconductor processing needed to be developed for many years to enable Gigabyte levels of storage to be economical. Such high density memory requires considerable understanding of underlying physics in the device to make such miniaturisation work properly.

Microelectronics and packaging: To realise such compact products has pushed circuit integration levels and packaging technology to the limit. In school you might encounter 8- or 16-pin dual-inline chip packages. In modern product design you are more likely to encounter 4000-pin ball-grid array packages that push printed circuit board production and soldering to the limit. Understanding the fluid mechanics involved in solder flow, for example, has been essential in increasing package densities to the required level.

Full colour displays: The standard colour LCD display employs liquid crystals, transparent electrodes, and transistors fabricated on glass panels. It took many years of development to make them so clear and bright. And yet, there is every chance that one day you may be reading this on a roll-up colour display based on electronic ink.

Digital representation of analogue signals: music is analogue; the sound from an instrument creates a continuously-varying voltage waveform at the output of a microphone. However, modern file storage and processing is digital and the music must be converted to a binary (ones and zeros) representation. Expertise is required therefore to design analogue-to-digital and digital-to-analogue converters, and deal with optimum sampling rates and data formats.

Data compression: The number of songs that can be stored is approximately 10X larger if MPEG compression technology is employed. This means that powerful mathematical algorithms must be somehow implemented on the silicon chip. When playing a track, the compressed MP3 file must be converted back to digital audio samples in real time.

Embedded systems design: Electronic engineers are needed to expertly design an integrated system-on-chip solution, and engineers at the electronics/computing interface are required to perform low-level programming for interfacing blocks together. At a higher level, a programmer needs to implement the user interface and menu, whilst using a minimum of chip resources (programme memory, etc).

Industrial product design: This part of the design task is about the style and ergonomics of the product. The designer needs a thorough knowledge of materials and manufacturing processes in order to create a stylish design that is economical to produce. Design for manufacturability (DFM) and design for the environment (DFE) are important themes of this activity. The designer needs to consider how the whole ensemble of electronic and mechanical components can be assembled, and even how it can be disassembled for recycling of key parts and materials. This part of the design process will also involve mechanical engineers and production engineers.

This overview has just scratched the surface of everything that is involved in designing an MP3 player and taking it into production. However, even from this overview it should be obvious that no one person has all the skills needed to accomplish the task. In fact, everyone involved in the design needs to be an expert in his or her specialist field. But, as we specialise more we find we start to know "everything about nothing": In other words, an inevitable aspect of becoming a world expert in (say) semiconductor physics is that the brain has no capacity left to know much about the details of (say) the MPEG compression algorithms. This concept is summarised in the "pyramid of knowledge" illustrated in Figure 8. This phenomenon is probably the source of the myth of the 'absent-minded Professor', although there is some truth in it since focussing too hard, or for too long, on a single very advanced technical problem can definitely cause a person to lose a grip on reality!

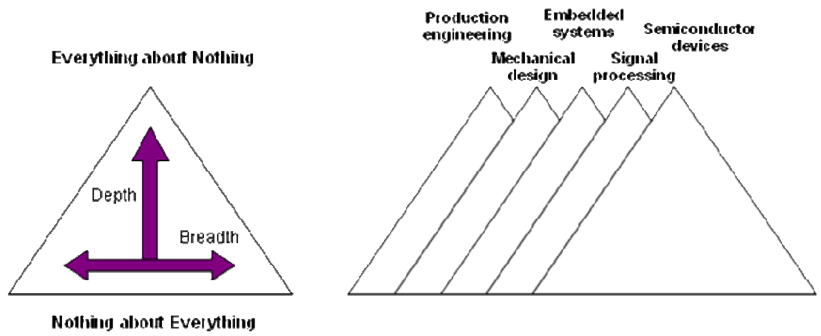


Figure 8 The pyramid of knowledge applied to the design of an MP3 player or similar electronic product

6 The consumer electronics business

The consumer electronics business is extremely competitive; customers now demand better and better products every year and expect the price to fall. The need for standardisation makes it difficult to introduce any new medium without extensive industry-wide consultations; format wars like VHS vs. Betamax, Blu-Ray vs. HD-DVD, and 8mm vs. VHS-C can be extremely damaging. Competing companies might lower their prices below an economically-viable level to encourage consumers to adopt their standard. Sooner or later, there have to be winners and losers; sometimes it is the technically superior technology that loses. Fortunately, with wireless communications standards there is some government control because of spectrum regulation: Thanks to the tireless efforts of engineers on committees (especially those of the IEEE – The Institute of Electrical and Electronics Engineers, Inc.) there is a high degree of standardisation. However, this is never a straightforward process as licensing fees for crucial technologies might encourage bigger companies to develop proprietary standards of their own.

Consumer electronics is a tough business but, on the other hand, it can also be extremely profitable. In 2006, the top ten consumer electronics companies were, in alphabetical order; Alps, LG, Matsushita, Philips, Pioneer, Samsung, Sanyo, Sharp, Sony and Toshiba. Samsung, the biggest, had sales of £45Bn and an operating profit of almost £5Bn [Samsung Electronics Annual Report 2006]. Add to these companies many other familiar names like Apple, Intel, Motorola, Westinghouse, Hewlett Packard, Dell, RCA/Thomson and Polaroid. Then, consider the rise of Chinese companies: there are many big Chinese companies (e.g. Panda Electronics, Changhong, BOE) that carry out manufacturing for the aforementioned companies. There are many others that design and manufacture products that are then badged by other, better-known, brands for retail. Some of the notable manufacturers are Alco, Nam Tai, Elite, WKK Holdings, Wong's, SMT, Whitways, and Computime. As an indication of the scale of this business, more than 100 million DVD players were manufactured in China in 2006, a large proportion of them badge-engineered. There is an increasing trend for companies based in South East Asia to develop their own brand in the retail marketplace, with companies including Lenovo, Haier, Xcute, Ningbo BIRD, Lite-On, Skyworth, Amoi, SVA and BenQ leading the way.

In 2006, Samsung's most profitable division, by a considerable margin, was the semiconductor manufacturing one. It is important, therefore, not to concentrate only on the big name brands, but also to know which companies are the leaders in semiconductor chip design and manufacturing as well. China is an enormous powerhouse of electronics manufacturing and Table 2 lists the top 10 suppliers of semiconductor chips into the China EMS (Electronics Manufacturing Service) industry. In semiconductor chips alone, the Chinese EMS market was worth >$20Bn in 2005 and the total value of the Chinese EMS industry in 2007 was estimated to be over $70Bn. Taiwan has great strength in semiconductor and component manufacturing and two of the largest silicon manufacturing businesses – UMC and TSMC - are based there. UMC and TSMC specialise in manufacturing wafers for other companies. This highlights the fact that there are several business models in the electronic product design and manufacture business:-

Vertically integrated company; this is the traditional model where a large company makes everything from the semiconductor devices to the branded consumer products
Contract manufacturer (EMS); this is a company that concentrates solely on providing an electronics manufacturing service for its customers.
OEM; An Original Equipment Manufacturer builds components and assemblies that are supplied to another company that assembles them into a complete product.
ODM; An Original Design Manufacturer designs and manufactures a product that is then sold under another brand name. This is often referred to as "badge engineering".
Chip manufacturer; A company that specialises is designing sophisticated high-value integrated circuits (ICs) and manufacturers them for sale as components.
Fabless design house; A company that specialises in designing ICs and supplies them as components, but subcontracts out the chip manufacture itself.
Chipless design house; A company which has design techniques that are sufficiently novel for other companies to want to pay to use them in their own chip designs. The UK-based company ARM is the best example of this; ARM's processors are used in a vast number of consumer products but they supply the design, which is then integrated within a larger system-on-chip by the customer.
Foundry; A company that carries out semiconductor manufacturing for customers but does not necessarily design products of its own.

Table 2. The top ten semiconductor suppliers to the China EMS industry. © iSupply Corp. 2006, used with permission.

		2005 Revenue $M
1	Intel	5,774
2	Texas Instruments	2,270
3	STMicroelectronics	1,799
4	Samsung Electronics	1,741
5	Philips Semiconductors*	1,720
6	Toshiba	1,435
7	Hynix	1,243
8	Freescale Semiconductor	1,239
9	Infineon Technologies	1,000
10	Micron Technology	704

* NXP was established in 2006

7 Product teardowns – reverse engineering

"Reverse engineering" means taking a competing product apart and finding out, in detail, how it works and how it was built. There are a number of reasons for wanting to do this; firstly, within the limits of the law, you can gain valuable ideas about how to improve your own design. Secondly, you can find out who your competitor does business with - who they buy their chips and other components from. Knowing this will help you choose your own business partners and improve your competitiveness. Finally, by studying the competitor's product you can find out whether any of your protected ideas have been illegally copied.

This last point is particularly important since intellectual property (IP) is one of the most prized assets of a high technology company. As a result, the information from teardowns has considerable commercial value. However, to fully reverse engineer a product is extremely time-consuming and so it is best left to one of those companies that specialise purely in this "teardown" business, such as Portelligent, Semiconductor Insights, and iSupply. The information that is supplied in a product teardown from iSupply includes:-

- Complete parts list & component count (product Bill of Materials)
- Detailed manufacturing cost analysis
- Block diagram
- Detailed step-by-step disassembly in high-resolution color photographs
- Power measurements
- Circuit board & packaging metrics
- Product specification sheet
- Interesting electronic features and packaging concepts

Figure 9 shows a screenshot of part of an iSupply teardown report: The typical cost of a 40 page product teardown is $5000. However, many products will use highly-integrated dedicated ICs. So, to properly study the product may require complete reverse engineering of the chip itself; the integrated circuit will be stripped down in a cleanroom, layer-by-layer, and the circuit diagram painstakingly re-created. Only then is it possible to establish whether the competitor's chip infringes on your own intellectual property.

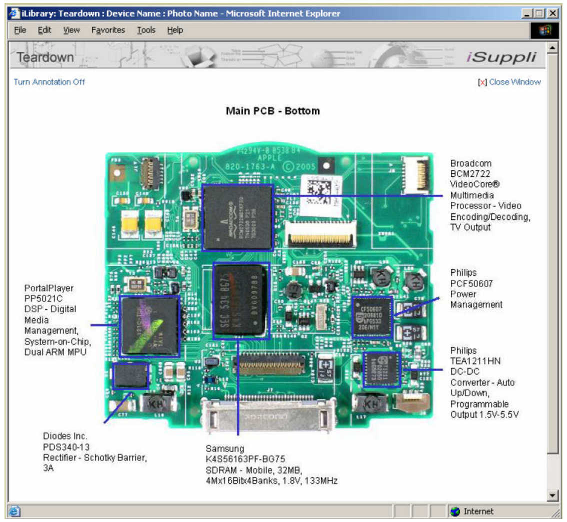
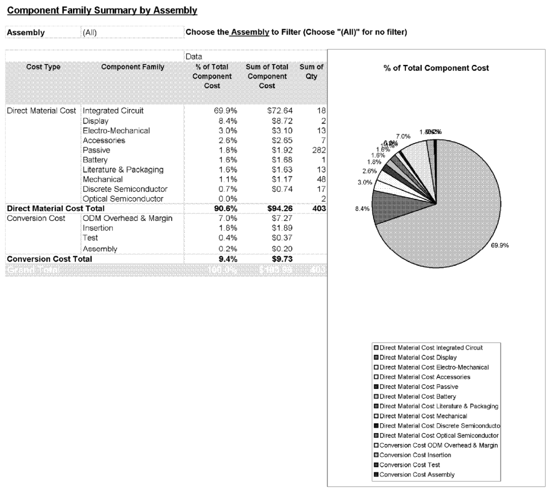


Figure 9 Screenshot of an iSupply teardown report. Courtesy of iSupply, all rights reserved.



Component Family Summary by Assembly

Assembly	(All)	Choose the Assembly to Filter (Choose "(All)" for no filter)		
		Data		
Cost Type	Component Family	% of Total Component Cost	Sum of Total Component Cost	Sum of Qty
Direct Material Cost	Integrated Circuit	69.9%	$72.64	18
	Display	8.4%	$8.72	2
	Electro-Mechanical	3.0%	$3.10	13
	Accessories	2.6%	$2.65	7
	Passive	1.8%	$1.92	282
	Battery	1.6%	$1.68	1
	Literature & Packaging	1.6%	$1.63	13
	Mechanical	1.1%	$1.17	48
	Discrete Semiconductor	0.7%	$0.74	17
	Optical Semiconductor	0.0%		2
Direct Material Cost Total		**90.6%**	**$94.26**	**403**
Conversion Cost	ODM Overhead & Margin	7.0%	$7.27	
	Insertion	1.8%	$1.89	
	Test	0.4%	$0.37	
	Assembly	0.2%	$0.20	
Conversion Cost Total		**9.4%**	**$9.73**	
Grand Total		100.0%	$103.99	403

Figure 10 Part of a bill of materials (BOM) summary from iSupply, Courtesy of iSupply, all rights reserved.

Some Internet Links

This list is still in its infancy. If you find any other good ones, please let me know.

www.howstuffworks.com
Excellent guide to how many things work, at a simple level.
Record-breaking number of pop-ups. Beware!

http://physicsweb.org/resources//Education/Interactive_experiments/Optics/
Diffraction demo

http://www.universityphysics.com/
Various physics explanations

http://www.ieee-virtual-museum.org/
Let's Get Small: The Shrinking World of Microelectronics
Microwaves: From Your Kitchen to the Edges of the Universe

http://www.ce.org
Consumer Electronics Association; US based
Heavily involved with standards and US Government policy

http://www.homecinemachoice.com/
Masses of articles on TV/audio, aimed at the consumer.

http://www.whathifi.com

http://www.techonline.com/
Requires registration; mostly more advanced info on things like Bluetooth

http://www.audiovideo101.com
useful dictionary of terms

http://www.london-fire.gov.uk/fire_safety/recalls/
Surprisingly long list of electronic goods that may pose a fire risk and have been recalled!

http://www.datapro.net/
Connector and cable supplier; lots of info on video and audio connectors and signal formats. Handy list of PAL/NTSC/SECAM by Country.

http://www.microcinema.com
Some info about DVD player compatibility for PAL/NTSC

http://www.flattvpeople.com/tutorials/lcd-vs-plasma.asp
Comparison of LCD and Plasma TV practicalities

http://www.pctechguide.com/index.htm
Excellent guide to PCs, digital cameras, scanners, etc.

www.discovercircuits.com

www.intel.com
History of Intel microprocessors. Info about fabrication technology.

BOOKS for further reading

Recommended Texts
Category B
1. The Digital Consumer Technology Handbook
- A Comprehensive Guide to Devices, Standards, Future Directions, and Programmable Logic Solutions
ISBN: 0-7506-7815-1
Author: Amit Dhir
Publisher, Newnes (Elsevier), 2004

2. Consumer Electronics for Engineers
ISBN 0-521-588170
Author: Hoff
Publisher, Cambridge University Press

Other books in the Edward Boyle Library Level 11

Television fundamentals
John Watkinson.
Oxford : Focal Press, 1994.

Digital video broadcasting : technology, standards, and regulations
Ronald de Bruin, Jan Smits.
Boston, Mass. : Artech House, c1999.

Basic TV technology
Robert L. Hartwig.
Oxford : Focal, 2000.

Colour television theory : system principles, engineering practice and applied technology
Geoffrey H. Hutson, Peter J. Shepherd and W.S. James Brice.
London : McGraw-Hill, c1989, 2nd ed.

Automotive electrics and electronics
Warrendale, PA : SAE Society of Automotive Engineers, 1999
Stuttgart : R. Bosch. 3rd ed.
EBL 11 Mechanical Engineering E-7 BAU

Hillier's fundamentals of automotive electronics
V.A.W. Hillier.
Cheltenham : Stanley Thornes, 1996. 2nd ed.
EBL 11 Mechanical Engineering E-7 HIL

Coding, communications, and broadcasting
edited by Paddy Farrell, Michael Darnell and Bahram Honary.
Published Baldock : Research Studies Press, c2000

Newnes audio & hi-fi engineer's pocket book
Vivian Capel.
Published Oxford : Newnes, 1994.
3rd ed

Muncaster, Roger.
A-level physics / Roger Muncaster.
Published Cheltenham : Stanley Thornes, c1989. 3rd ed.
EBL 11 Physics A-1 MUN

Convergence technologies for 3G networks : IP, UMTS, EGPRS and ATM
Jeffrey Bannister, Paul Mather, Sebastian Coope.
Published Chichester : Wiley, 2004.