Electronic Signals and Systems

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List of Computer Programs

The following BASIC programs appear in the main text

All programs have been developed and tested on an Amstrad personal microcomputer. They use relatively few of the available BASIC instructions, and should run on a wide range of other machines with only minor modifications.

Most programs include both a *plot option* and a *print option* for the output. The relevant program lines may be included or omitted, as required. The plot options use the Amstrad BASIC instructions CLS (clear screen), PLOT (plot pixel at stated X, Y coordinates), and DRAW (draw line to stated X, Y coordinates). They are based on a screen resolution of 640 × 400 pixels. All plots have been kept simple, and it should be straightforward to produce equivalent graphical outputs on other computers.

In most cases programs are based on mathematics developed in the accompanying text. Their structure and content should therefore be clear to the reader. The only exceptions are program no. 5 and program no. 8. These are presented without detailed explanation, and used to illustrate important techniques described in more general terms in the text.

Preface

This book is designed as an introductory text in electronic signals and systems for the early stages of degree courses in universities and polytechnics. Its level and scope should make it suitable not only for electronic and electrical engineering courses, but also for those covering other branches of engineering, physics, and computer studies. The initial pace of the book is deliberately gentle. Students with very little previous knowledge of electronics should find its first few chapters quite easy to follow.

Pressure on the electronic and electrical syllabus continues to grow. New material, particularly in microelectronics and computing, constantly competes for the student's time. Yet most lecturers (and employers) are reluctant to see important topics such as linear circuit theory, communications, and control seriously reduced. A partial solution to the problem is to teach Signals and Systems early in the course, using it as a foundation for much that follows. This can substantially reduce double-teaching. It also has the great intellectual advantage for the student of emphasising links between the many branches of electronic engineering.

Quite a number of Signals and Systems textbooks have appeared in recent years. However, in my view these are often too difficult for the early stages of an undergraduate course. Furthermore, many use a 'black box' approach. Students get much of their initial motivation from practical work with circuits, and they appreciate a Signals and Systems approach which illustrates ideas with circuit applications. I have decided to meet this need by including many examples based on operational amplifier techniques. These have the advantage of requiring no detailed understanding of active devices or circuits.

The book offers a number of features

A unified treatment of continuous-time and discrete-time signals and systems.
A thorough introduction to time and frequency domain analysis.
Circuit examples—passive and active, analog and digital—to illustrate the text.
Worked examples in the text, problems at the end of each chapter, and solutions at the end of the book.
BASIC computer programs, integrated with the main text, to illustrate important concepts and applications.

The last item deserves a little explanation. Digital computers are becoming more and more important in teaching, and many students now have the use of a personal microcomputer. All programs in this book are suitable for such machines, and I believe that most readers will gain a lot by using them. I should add that the programs are included as aids to understanding signals and systems, *not* computer programming. I make no claims at all for them in this latter respect.

In slightly more detail, the first two chapters are intended as a gentle introduction to the background and scope of the subject. I have, with some misgivings, decided to summarise the basic circuit ideas needed for this book in chapter 1. The aim here is to make the book self-contained. I have emphasised in the text itself that these sections are in no sense to be regarded as a course in circuit theory! Chapters 3 to 6 offer a fairly conventional account of the basic tools of signal and system analysis. Convolution is covered *before* frequency-domain transforms, because discrete-time convolution is so straightforward and illuminating. If the student understands it well, such notions as the transient and steady-state response of a system, stability, causality, and so on, present very little difficulty. I hope that these first six chapters form a coherent and readable introduction to linear signal and system theory. I have tried to suggest and include plenty of applications, and have commented on some of the practical problems of design. The chapters contain many cross-references, and should preferably be studied in the correct sequence.

Chapter 7 consolidates and extends ideas about feedback, and introduces a number of important applications. I have tried to show how the major characteristics of negative and positive feedback are put to use in a variety of practical systems—analog and digital. Chapter 8 on signal processing first covers signal sampling and reconstitution with some care. It then outlines the processes of signal truncation and windowing, and introduces analog and digital versions of the widely used Butterworth and Chebyshev filter families. These last two chapters are independent of one another, although each relies heavily on material in chapters 1 to 6. They may therefore be included, or omitted, as required.

It would be impossible to list all the sources which I used, consciously or unconsciously, in the writing of this book. I have referred to numerous books on signal analysis, system theory, circuits, and filters. I have also drawn on personal experience, lecture notes generated over a number of years, and unrecorded conversations with colleagues. I gratefully acknowledge all these contributions. I also wish to make a few more specific acknowledgements. Dr W.A. Atherton's excellent book on the history of electrical and electronic engineering, *From Compass to Computer* (Macmillan, 1984), suggested the use of the photographs and historical material in chapter 1. I am grateful for permission from the Bell Laboratories, the Siemens Museum, the Marconi Company, and *Punch* magazine, to include them. I should finally like to record my thanks to Jeana Price for all her work on the typescript; and to express gratitude to those, near and far, without whose support this book would not have been completed.

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1 Introduction

"It is a good thing to have two ways of looking at a subject, and to admit that there are two ways of looking at it."

James Clerk Maxwell (1831–1879),
whose electromagnetic theory
predicted 'wireless' communication

1.1 Historical perspectives

The early pioneers of electronics and telecommunications would surely be astonished to see the variety of uses of modern electronic engineering. Even as late as 1950, the impact of electronics on the average household in the industrial world was limited to a telephone, a radio receiver, and perhaps a gramophone. We now also have televisions, home computers linked to data and communications networks, pocket calculators, video and audio tape recorders and electronic watches—and we increasingly use electronics in our domestic appliances, for the control of heating systems, and in our cars. Such uses are apparent to everyone. But of course electronics has also entered schools and universities, offices, factories, and hospitals. Ships and satellites navigate with it, aircraft cannot fly without it. Government departments and business organisations rely upon it, in the form of digital computers, for information storage and retrieval. The list seems endless, and grows longer every year.

The reasons for all this are not hard to discover. Electronics can detect, measure, control, process, and communicate. It does all these things quietly, cleanly, and very quickly. It is also becoming increasingly cheaper. The valve receivers used by amateur radio enthusiasts in the 1920s cost, in real terms, perhaps 50 times as much as their modern solid-state counterparts. The digital computers of the 1950s used hundreds or thousands of expensive thermionic valves, gave off large amounts of heat, and were very unreliable. Essentially research machines, they were so expensive that only large organisations could afford them. Today the same computing power is available to the individual for less than the price of a pair of shoes. The same story is repeated with a wide variety of electronic systems—as a result, of course, of the very rapid development of semiconductor and microelectronic technology since about 1960.

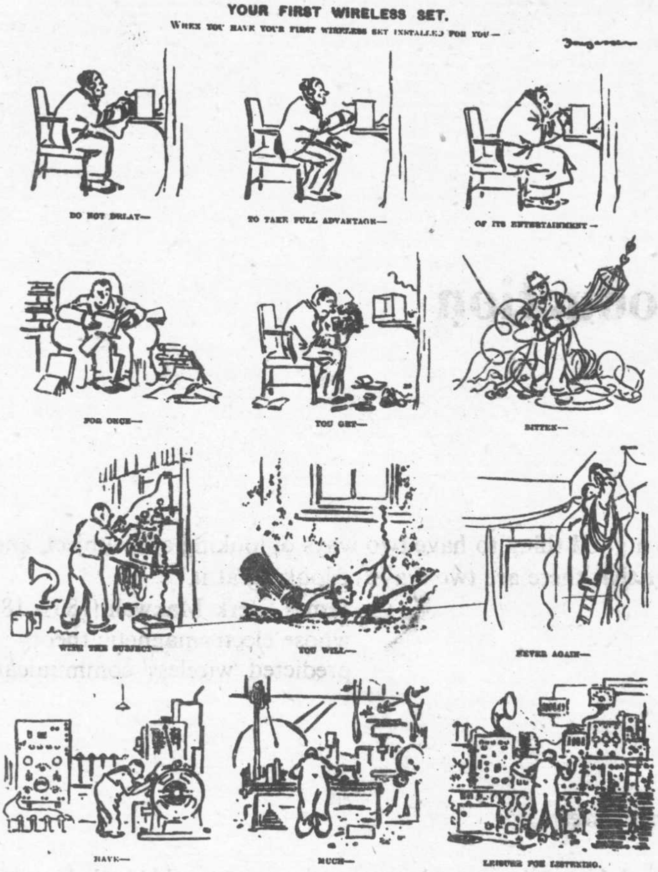

Figure 1.1 The cumbersome technology of early radio: a cartoon from *Punch* magazine, 1924 (courtesy of *Punch* magazine).

This book is about electronic *signals*, and electronic *systems*. And to put the present situation into a fuller historical perspective, it is helpful to consider the early development of telegraphy and telephony.

Optical transmission and coding of signals and messages—mainly for the purposes of warfare and defence—were current in antiquity, and the idea of a binary code had already been mentioned in the early 17th century. However, it was the systematic development of the electric telegraph in the 19th century which really laid the foundations of so much of our present electrical and electronic technology. Much of the early work stemmed from Oersted's crucial discovery, in 1820, of the magnetic effect of an electric current. More than 10 years were then to elapse before Gauss and Weber in Germany, and Henry in the USA, demonstrated electromagnetic signalling systems working over cables a kilometre or two in length.

Subsequent commercial development of the telegraph in Britain is associated with the names of Wheatstone and Cooke, and in the USA with that of Morse, who remarked to his friend Professor Gale of New York University in 1837 that if he could work his telegraph through ten miles of wire, he could work it round the world. Ambitious though the claim was, it rested on two very sound ideas: that a signal or message coded into just two basic types of symbol or

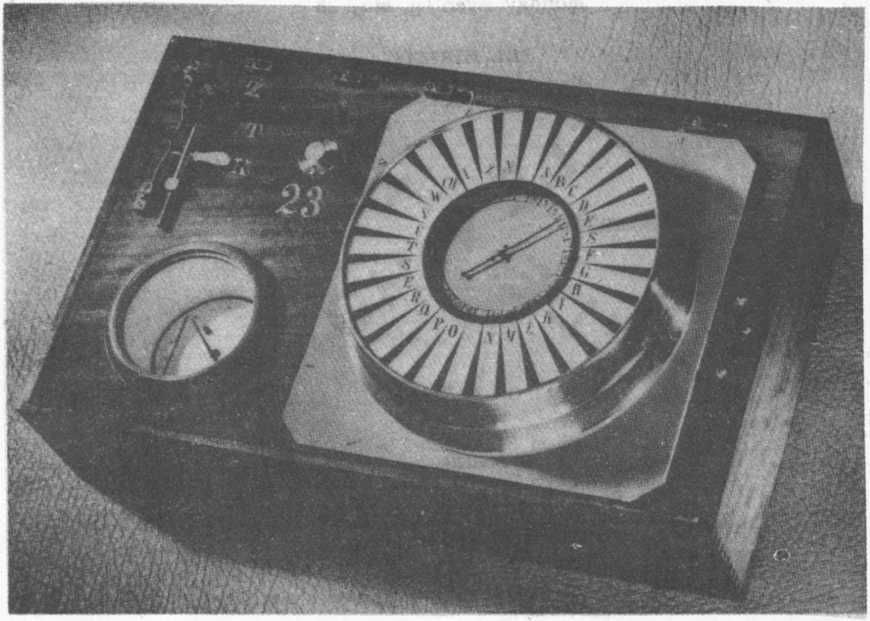

Figure 1.2 An early example of communication technology: the Siemens needle telegraph ot 1847 (courtesy of Siemens Museum, Munich).

character (such as 'dot' and 'dash') was inherently immune to electrical disturbance during transmission; and that even if such simple symbols *were* degraded to some extent, they could readily be regenerated at various 'repeater stations' spaced along the cable route. It is essentially these same two notions which underpin the massive development in our own time of what we now call digital communications systems.

The early telegraph engineers realised that, as cable lengths increased, a pulse signal such as a dot or a dash became spread out and delayed in time at the receiving end, because of the presence of resistance and capacitance in the cable. This meant that closely spaced symbols could not be separated at the receiver, and the message was lost. Kelvin's famous paper to the Royal Society in London in 1855 established the mathematical basis of such effects, which were of particular relevance to the development of a successful transatlantic telegraph. We now see Kelvin's work as an important example of the analysis of the effects which a *system* can have on the *signals* which it transmits or processes. Engineers are supposed to be ingenious, and it soon occurred to them that it might be possible to alleviate the undesirable 'spreading effect' of a long cable by modifying the receiver. Heaviside, writing in the *Philosophical Magazine* of 1874, showed that a valuable improvement in pulse shape could indeed be obtained by placing capacitors in parallel with the receiver. Since each pulse was now less spread out, more dots and dashes could be successfully transmitted in a given time, thus increasing the message capacity of the cable.

Further important developments in the theory and practice of telegraphy by pulse code took place in the later decades of the 19th century. However, we now turn to the direct electrical transmission of speech by a continuously varying, analog waveform—initiated by Bell's famous patent of 1876.

CITY HALL, LAWRENCE, MASS.

Monday Evening, May 28

THE MIRACLE

TELEPHONE

WONDERFUL DISCOVERY

TELEPHONE

OF THE AGE

Prof. A. Graham Bell, assisted by Mr. Frederic A. Gower, will give an exhibition of his wonderful and miraculous discovery **The Telephone,** before the people of Lawrence as above, when Boston and Lawrence will be connected via the Western Union Telegraph and vocal and instrumental music and conversation will be transmitted a distance of 27 miles and received by the audience in the City Hall.

Prof. Bell will give an explanatory lecture with this marvellous exhibition.

Cards of Admission, 35 cents
Reserved Seats, 50 cents
Sale of seats at Stratton's will open at 9 o'clock.

Figure 1.3 A publicity notice for one of Alexander Graham Bell's demonstrations of the telephone, 1877 (courtesy of AT & T Bell Laboratories).

The analog principle, exemplified by the Bell telephone, seemed at that time nearly ideal for speech transmission, since the rate at which pulsatile dots and dashes could be transmitted over even very short cables was severely limited by the available technology. Further developments were greatly stimulated around the turn of the century by Marconi's experiments in radio, providing a practical sequel to the earlier theoretical studies by Maxwell and the pioneering investigations of Hertz. Other major contributions were made by Fleming and Lee de Forest, who developed the first vacuum valves for detecting and amplifying the very weak signals entering a radio receiver. By the 1920s, however, it was realised that electrical interference or 'noise'—arising not only along the transmission path but also, inevitably, in the receiver itself—formed a fundamental limitation to the rate at which messages could be sent through any communications 'channel'. The separation of a wanted signal from such noise using electrical filters became, and has remained, an important application of electronic systems.

In the early years of telephony, its underlying engineering principles seemed clearly different from those of telegraphy, concentrating as they did on continuous analog waveforms rather than 'digital' pulses. However, during the Second World War telephony in certain applications became, in a quite literal sense, a form of telegraphy. In modern terminology, the system underwent an analog-to-digital conversion, whereby the speech waveform was sampled, coded into digital pulses for transmission, and reconstituted into analog form in the receiver. We shall have more to say later about this approach, which is now called Pulse Code Modulation (PCM) and is widely used by telephone authorities around the world. At this point, we merely note that

Figure 1.4 One of Fleming's experimental diodes, 1906 (courtesy of the Marconi Company Ltd).

its major advantage is immunity from noise and interference—as noted by Samuel Morse back in 1837! So the modern view is that telegraphy and telephony, formerly seen as distinctive types of communication, are inextricably linked in both theory and practice.

The last 50 years or so have seen an enormous expansion in the practical applications of signal and system ideas. For example, the development of radar before and during the Second World War initially drew upon, and in turn made major contributions to, the theory of signals and communications. Another major application area is Automatic Control, which also developed rapidly in the 1940s out of the need to design effective systems for such tasks as automatic gun-laying and anti-aircraft tracking. Also the field of Signal Processing, which is concerned with the modification of signals in a whole variety of ways by electronic circuits and computers, has found important applications in such diverse areas as communications, seismology, biomedicine, and the enhancement of pictures and images.

The application of signal and system concepts has now become so widespread that we should no longer think of the word 'signal' as necessarily representing a message to be sent from one place to another. It can just as well represent almost any type of information, data, or physical variable—the variation of bank interest rate, the midday temperature at a certain place, or the blood velocity in an artery. Provided such 'signals' may be converted into electrical waveforms, or entered as data into an electronic computer, we may use the ideas of signal and system theory to analyse and process them in a wide variety of valuable ways.

1.2 Continuous and discrete signals and systems

The ideas and applications of electronic engineering often seem to fall into two rather distinct camps. On the one hand, there are analog circuits, composed of elements such as resistors, capacitors, inductors, and amplifiers; on the other hand, there are digital circuits and computers, built up from a number (and often a very large number) of logic gates. Analog circuits deal mainly with such continuous waveforms as mains voltages and currents, or the voltage output from a microphone. Digital circuits appear to be concerned with what are essentially switching or control problems, such as the sequencing of a set of traffic lights.

It is a major aim of this book to show the reader that such distinctions between the applications of continuous and discrete electronics are in many ways artificial. A large number of engineering design problems can be, and indeed are, solved by either analog or digital methods, or by a combination of the two.

We have already seen how the history of telegraphy and telephony underlines the fact that speech messages can be transmitted either as digital pulses or analog waveforms. Let us consider two other practical examples of this essential equivalence between the analog and digital approaches.

(1) For almost exactly a century following Edison's invention of the phonograph in 1877, records of music and speech for home entertainment were based exclusively on analog techniques. During replay, a needle or stylus followed a fluctuating groove on the record's surface. This analog movement was transformed into a corresponding sound pressure variation—in the early years by a flared horn, later by a loudspeaker driven by an electronic amplifier.

In about 1982, however, digital records also became available. In this PCM method, the music or speech signal is first converted into a binary pulse code, and then impressed on the record as a series of minute indentations representing '1s' and '0s'. It may be read off the disc by laser. Of course, the pulse code cannot be interpreted by the human ear, so must be converted back to analog form before delivery to loudspeakers.

(2) In hospitals, electroencephalograph or EEG signals (sometimes popularly referred to as 'brainwaves') are often recorded from the surface of the scalp; for example, in patients with epilepsy, or for monitoring the effects of drugs and anaesthetics. These electrical signals are amplified, processed, and displayed, often on a multichannel chart recorder. It is sometimes valuable for diagnosis to separate the signal into certain frequency ranges, or bands, before display.

For many years, such 'frequency analysis' was performed by analog wave filters, consisting of such circuit elements as resistors, capacitors, inductors, and amplifiers. However, these filters were bulky, expensive, and hard to calibrate. With the advent of cheap computers it has become common to achieve equivalent filtering by digital means.

Figure 1.5 Bardeen and Brattain's first point-contact transistor, 1947 (courtesy of AT & T Bell Laboratories).

The EEG signal is first sampled and converted into a binary code, and then fed into a computer and processed.

Of course, we must not assume that because a digital solution to a particular problem is possible *in principle*, it is necessarily preferable *in practice*. There are many factors involved in the design of an electronic system to solve a particular engineering problem. These include technical performance, speed, cost, equipment volume, availability of components and spares, ease of maintenance, and so on. It nevertheless remains a very important idea that many design problems may in principle be solved by either analog or digital methods.

The above ideas are summarised by figure 1.6. Part (a) shows an analog, or continuous, system fed by a continuous input $x(t)$ and producing a continuous output $y(t)$. The system might be a cable or other transmission medium, or a unit designed to process or modify the signal in some way. In this particular case it has the properties of a *low-pass filter*, that is to say a unit which passes the low-frequency (that is, the slowly fluctuating) components of the input signal, but suppresses high-frequency ones (which might here represent rapid unwanted disturbances or 'noise'). In figure 1.6(b) is shown a digital, or discrete, system which processes an input signal $x[n]$ composed of a set of discrete sample values. We may normally think of these as simply representing the numerical value of the input at equally spaced instants of time. The output $y[n]$ is also in sampled form. The system may well be a digital computer, programmed in this case to