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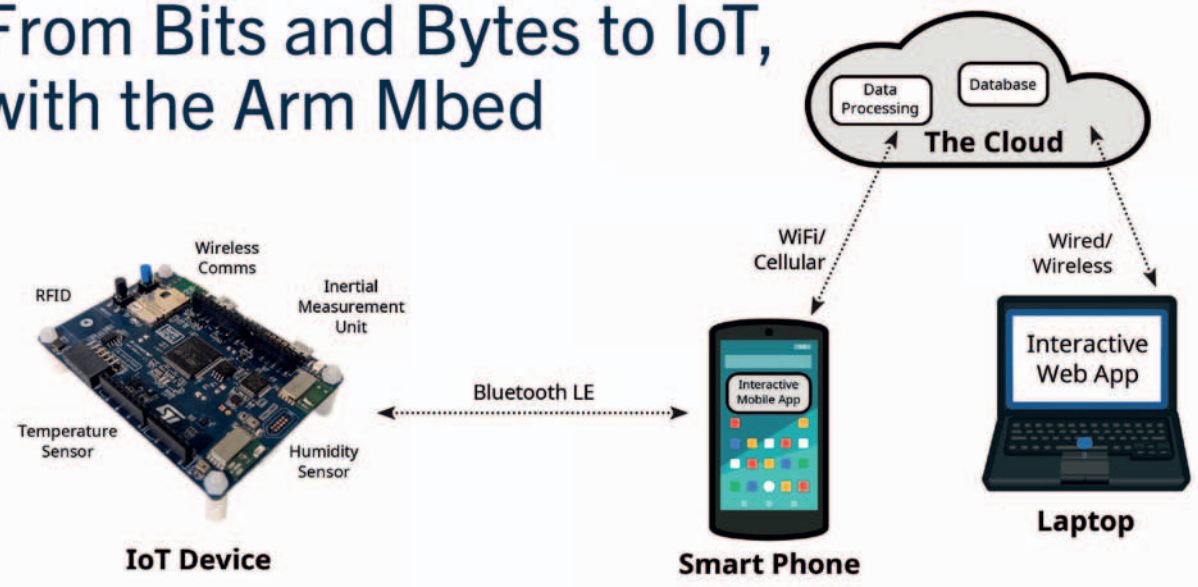
FAST AND EFFECTIVE EMBEDDED SYSTEMS DESIGN

From Bits and Bytes to IoT, with the Arm Mbed



Tim Wilmshurst, Rob Toulson and Tom Spink

Fast and Effective Embedded Systems Design

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Rob Toulson
Tim Wilmshurst
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Introduction

It's now eleven years since the first edition of this book was published, and seven years since the second. Microprocessors are of course still everywhere, providing "intelligence" in cars, mobile phones, household and office equipment, TVs and entertainment systems, medical products, aircraft—the list is endless. Those everyday products, where a little computer is hidden inside to add intelligence, are called *embedded systems*.

It is still not so long ago that designers of embedded systems had to be electronics experts, or software experts, or both. Nowadays, with user-friendly and sophisticated building blocks available for our use, both the specialist and the beginner can quickly engage in successful embedded system construction and design. One such building block was the *Mbed*, a self-contained microcontroller development board, launched in 2009 by the renowned computer giant Arm. The Mbed was the central theme of the first edition of this book, and through it all the main topics of embedded system design were introduced.

Technology has continued its onward gallop since those earlier editions, and there is already much from the second edition which needs updating, rewriting, or replacing. The single Mbed device that we based the first book on has spawned an extended family of "Mbed-enabled" devices. An "ecosystem" of products, development tools, and community support has emerged, and the phrase "internet of things" (IoT) is now on everyone's lips. The creators of the Mbed, Arm, repositioned the Mbed concept, notably by placing it at the heart of their IoT developments. The original Mbed LPC1768 device, however, is still there, widely used and well established, in industry, among hobbyists, and in colleges and universities worldwide.

Alongside hardware developments, there has been stunning growth in software techniques. As part of the Mbed ecosystem, Arm have crafted a sophisticated operating system, an essential framework through which program development takes place. While in earlier editions we tried to restrict ourselves more or less to use of the C programming language, this is now no longer possible. The Mbed operating system requires some use of C++, as more advanced applications are encountered.

In light of all these changes, we as authors made a number of decisions regarding this new edition. We have retained the Mbed LPC1768, but recognize that it's approaching the end of its working life. Therefore, in parallel, we've introduced an alternative board, the Nucleo F401RE. You can work through the first 10 chapters of the book using either of these. As if two boards aren't enough, we introduce a third, the ST IoT discovery kit. We use this primarily for Chapters 11−13, the IoT part of the book.

In terms of content, we have dropped the audio and internet chapters to make way for a pair of explicitly IoT-focused chapters. There is also a completely new chapter on using the real time operating system, or RTOS.

Broadly, the book divides into three parts. Chapters 1 to 10 provide a wide-ranging introduction to embedded systems. These chapters aim to give full support to the reader, moving you through a carefully constructed series of concepts and exercises. They start from basic principles and simple projects, and move on to more advanced system design. The next three chapters, 11−13, sit clearly in the realm of wireless and the IoT. They start with the essential wireless techniques which underlie IoT capability, before building up a complex IoT example, linking sensors through intermediate devices right up to the cloud and back! Programming here also includes some Java and JavaScript. The final two chapters, mainly based on the Mbed LPC1768 but not depending on it, look inside the microcontroller to cover more advanced or specialist topics. They explain how some of the most fundamental microcontroller activities are undertaken and how they can be controlled—for example, setting clock speed or optimizing power consumption.

All this book asks of you at the very beginning is a basic grasp of electrical/electronic theory. The book adopts a "learning through doing" approach. To get started, you will need either the LPC1768 or the F401RE development board, an internet-connected computer, and at least some of the various additional electronic components identified. You won't need every single one of these if you choose not to do a certain experiment or book section. You'll also need a digital voltmeter, and ideally use of an oscilloscope.

Each chapter is based on a major topic in embedded systems. Each has some theoretical introduction, and may have more theory within the chapter. Most chapters then proceed as series of practical experiments. Have your board ready to connect up the next circuit, and download and compile the next example program. As your confidence grows, so will your creativity and originality; you will start to turn your own ideas into working projects.

You will find that this book rapidly helps you to

- Understand and apply the key aspects of embedded systems,
- Learn from scratch, or develop your skills in embedded C/C++ programming,
- Understand and apply the key aspects of the Arm Mbed operating system,

- Develop your understanding of electronic components and configurations,
- Produce designs and innovations you never thought you were capable of!

If you are a university or college instructor, then this book offers a "complete solution" for your embedded systems course. All three authors are experienced university lecturers, and had your students in mind when writing this book. The book contains a structured sequence of practical and theoretical learning activity. Ideally you should equip every student or student pair with an Mbed development board, prototyping breadboard, and component kit. These are highly portable, so development work is not confined to the college or university lab. Later in the course students will start networking their devices together. PowerPoint presentations for each chapter are available to instructors via the book web site, as well as answers to quiz questions.

Because the need for electronic theory is limited, this book is accessible to disciplines which would not normally aim to take embedded systems. The book is meant to be accessible to Year 1 undergraduates, though we expect it will more often be used in the years which follow. Students are likely to be studying one of the branches of engineering, physics, or computer science. The book will also be of interest to the practicing professional and the hobbyist.

The first ideas for this book came from Rob Toulson. When at Anglia Ruskin University in Cambridge, he started teaching with those new-fangled Mbed devices, working in close cooperation with the Mbed design team at Arm. Tim Wilmshurst—then at the University of Derby—joined to form a writing duo, and together Rob and Tim brought the first two editions to life. Tim then proposed, and has since led, development of the third edition. A new and welcome co-author, Tom Spink, joins the team for this edition. A lecturer in computer science at the University of St Andrews, Tom brings particular expertise in IoT and the software end of things. He and Tim are also authors of Arm Education MOOCs (massive open online courses) on embedded systems and IoT. Rob meanwhile has moved on from academia to become an active entrepreneur in digital music technologies (https://www.rt60.uk/), but has continued to play a supporting role in the new edition.

Because Tim has written several books on embedded systems in the past, a few background sections and diagrams have been taken from these and adapted for inclusion in this book. There seemed no point in "reinventing the wheel" where introductory explanations were needed.

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The authors would like to thank staff from Arm, including Donatien Garnier, Robert Iannello, David MacKenzie, and Andy Powers, for support in the development of this edition, and in earlier work on the MOOCs. Thanks also to those who develop and maintain content on the Mbed OS web site (https://os.Mbed.com/). We have made repeated use of this site and benefited from the many example programs therein.

We would further like to thank most warmly the following for their comments on draft chapters. They read and evaluated with care and attention, making valued suggestions for improvements to content or code, exposing lurking typos or technical inaccuracy, and brought their shared teaching expertise to how ideas should be presented and should flow. In alphabetical order they are Hammam Alsafrjalani of the University of Miami, Haitham Abu Ghazaleh of Tarleton State University, John Larkin of Whitworth University, Erik Petrich of the University of Oklahoma, and Atoussa Tehrani of Florida International University. Despite the value of these inputs, any errors or weaknesses in the book remain the authors' responsibility!

Thanks to Liz A of sweetclipart.com for the use of the car image in Figure 1.3.

Companion Web Site

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PART 1

Essentials of Embedded Systems, and Developing with Mbed

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CHAPTER 1

Embedded Systems, Microcontrollers, and Arm

1.1 Introducing Embedded Systems

1.1.1 What is an Embedded System?

We are all familiar with the idea of a desktop or laptop computer, and the amazing processing that they can do. These computers are general-purpose; we can get them to do different things at different times, depending on the application or program we run on them. At the very heart of such computers, we would find one or more *microprocessors*, tiny and fantastically complicated electronic circuits that contain the core features of a computer. These are fabricated on a single slice of silicon, called an *integrated circuit* (IC). Some people, particularly those who are not engineers themselves, call these circuits *microchips,* or just *chips.*

What is less familiar to many people is the idea that instead of putting a microprocessor into a general-purpose computer, it can also be placed inside a product which has nothing to do with computing, like a washing machine, toaster, or camera. The microprocessor is then customized to control that product. The computer is there, inside the product; but it can't be seen, and the user probably doesn't even know it's there. Moreover, those add-ons which we normally associate with a computer, like a keyboard, screen, or mouse, are nowhere to be seen. We call such products *embedded systems,* because the microprocessor that controls them is embedded inside. Because such a microprocessor is developed to control the device, in many cases those used in embedded systems have different characteristics from the ones used in more general-purpose computing machines. We end up calling these embedded computers *microcontrollers.* Though much less visible than their microprocessor cousins, microcontrollers sell in far greater volume, and their impact has been enormous. To the electronic and system designer they offer huge opportunities.

Embedded systems come in many forms and guises. They are extremely common in the home, the motor vehicle, and the workplace. Most modern domestic appliances, like a washing machine, dishwasher, oven, central heating, or burglar alarm, are embedded systems. The motor car is full of them, in engine management, security (e.g., locking and anti-theft devices), crash sensing, air-conditioning, brakes, radio, and so on. They are

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found across industry and commerce, in machine control, factory automation, robotics, electronic commerce, and office equipment. The list has almost no end, and it continues to grow.

Fig. 1.1 expresses the embedded system as a simple block diagram. A number of features appear; not every embedded system has all of them. There are one or more inputs from the external environment, for example, sensors providing voltages proportional to physical variables. The embedded computer runs a program dedicated to this application, permanently stored in its memory. Unlike the general-purpose desktop computer, which runs many programs, this is the only program it ever runs. Based on information supplied from the inputs, the microcontroller computes certain outputs, which may be connected to actuators and other devices within the system. Alternatively, that output may simply be data, transferred by cable or wireless to another subsystem elsewhere, or displayed to a user. The user may have further interaction—for example, via a keypad.

The actual electronic circuit, including the microcontroller and any electromechanical components, is often called the *hardware*; the program running on it is often called the *software*. There must be a supply of power to keep the circuits running. One other variable will affect all that we do in embedded systems, and this is time, represented as a dominating arrow which cuts across the figure. We will need to be able to measure time, make things happen at predetermined times, generate data streams or other signals with a strong time dependence, and respond to unexpected things in a timely fashion.

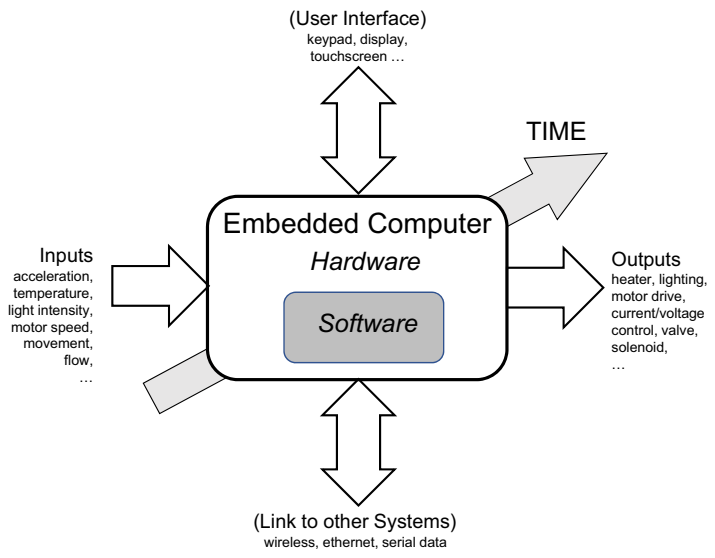

Figure 1.1
The embedded system.

A refrigerator controller provides us with an initial embedded system example. This has a temperature sensor in the main fridge compartment and one in the freezer. The user selects the required temperature or depends on default settings. Meanwhile, sensors are measuring the temperature in each fridge compartment. The embedded computer, a microcontroller, receives incoming signals from the sensors and control setting, compares these, and determines whether the compressor should be switched on or not. It will also display to the user the two temperatures measured, and may emit an alarm if a door is left open too long, or the temperature rises above a certain limit. In its traditional form the fridge does not have any external connection. However, a modern fridge may well be able to connect to the internet, so that the homeowner can check on its status while away—but more on this later.

1.1.2 Fast Forward to the Internet of Things

General-purpose computers, and now embedded systems, have become increasingly connected to the internet. The Internet of Things (IoT) is the name given to the resultant worldwide network of devices and artefacts—some everyday, some highly specialized—that are connected to the internet. These allow remote access to information that can be used to control and enhance diverse activities. The IoT generates huge quantities of real-time data that can potentially be accessed from anywhere in the world. IoT data now includes billions of sensors and databases that are made available for monitoring through the internet, from travel and transport data to environmental, medical, and industrial concerns large and small.

An integral part of the IoT is the concept of *cloud computing*, which uses servers and data memory storage locations that are only accessed through the internet. Companies such as Google, Microsoft, Apple, and Dropbox, among many others, provide their own cloud-based services, and it is anticipated that most, if not all, of our personal and professional data (and programs) will one day be stored in the cloud rather than on local computers and hard drives.

The IoT concept has expanded to include everyday objects attached to the internet. Examples include a washing machine that can alert the repair company to an impending fault, a vending machine that can tell the head office it is empty, a manufacturer who can download a new version of firmware to an installed burglar alarm, or a homeowner who can switch on the oven from the office or check that the garage door is closed.

1.1.3 The Electric Car—An Abundance of Embedded Systems

Technical developments in cars have been one of the driving forces behind the growth of embedded systems, with microcontrollers being applied in engine management, braking,

diagnostics, and many other things. Perhaps nowhere has this outpouring of embedded control been more evident than in the modern electric vehicle (EV), with battery replacing gas tank, and DC (direct current) electric motors replacing the internal combustion engine (see Fig. 1.2). Such a vehicle represents an excellent opportunity to apply and exploit embedded systems, using those little microcontrollers to their best advantage.

The possible categories of electronic control in the EV are shown in Fig. 1.3. Most of these will overlap, and other categorizations could be made. Each category contains numerous embedded systems, some controlling one or few variables, others managing a sophisticated array.

Imagine Fig. 1.1 implemented dozens of times within the EV, and think of the sensors and actuators in operation. The battery management will need to sense battery voltage and current, sometimes current flowing from battery to motors, at other times from motors back to battery due to kinetic energy recovery, then from charge point to battery when charging is taking place. Safety features will detect closure of seat belts in occupied seats, tire pressure, nearness of vehicle to potential obstacles, and lane following on a motorway or freeway. Environment control will sense internal and external temperatures and the temperature demanded by the driver and manage seat heating. Within most of these are actuators moving, heating, or lighting things they control. There is also an enormous flow of data, within and between the subsystems.

Figure 1.2
The electric car, rich in embedded systems.

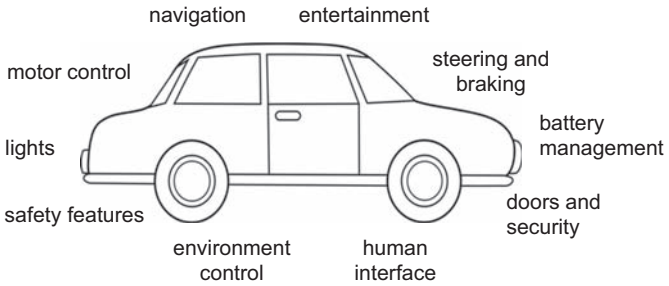

Figure 1.3
Electronic subsystems in the electric car.

Needless to say, data generated in the vehicle does not all stay within it. The owner is encouraged—indeed it's almost a necessity—to download a car-specific phone app, as seen in Fig. 1.4. This tells him or her many things, including the important features of whether the car is locked, the state of battery charge and available driving range, the

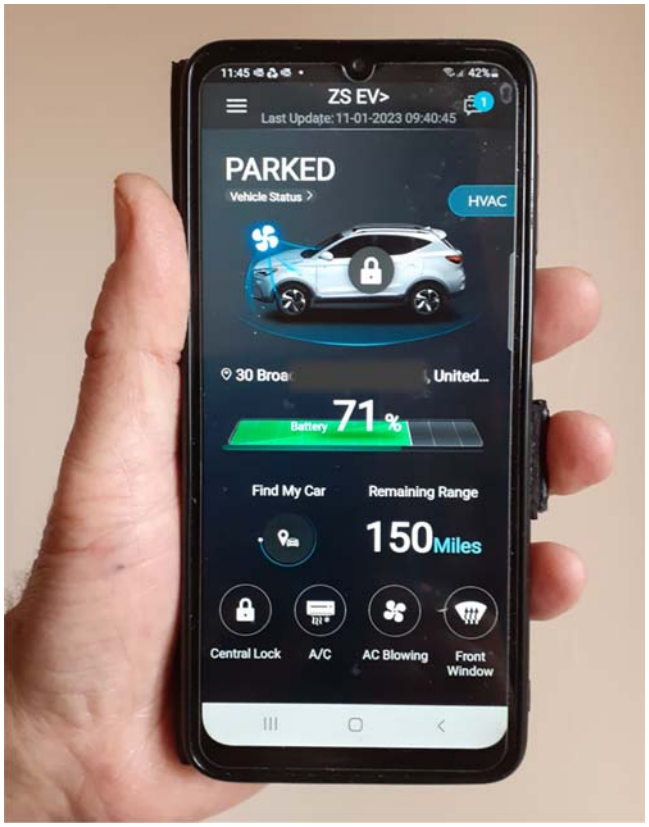

Figure 1.4
An electric car app.

vehicle state of health, and its location. From it the user can—if a charging cable is connected—start or stop charging. Also, on a cold day, the heating can be started and the windshield de-iced before a journey starts.

The actions just described place us firmly in the realm of the IoT. Data from the car has been transmitted wirelessly to the web, processed, and returned to the app, to be displayed in user-friendly form. Control data generated by the user with the app is then returned to the car for actuation.

This book takes us on a journey which—on completion—should allow you, the reader, to feel able to understand, apply, and even design the circuits and software found in embedded systems large and small. As each new chapter opens, we start at the beginning of that topic, initially with simple concepts.

This first chapter introduces or reviews many concepts relating to computers and embedded systems. It does this in overview form, to give a platform for further learning. We return to these concepts in later chapters, building on them and adding detail.

1.2 Microprocessors and Microcontrollers

Let's look more closely at the microcontroller, which sits at the heart of any embedded system. As the microcontroller is in essence a type of computer, it will be useful to get a grasp of basic computer details.

1.2.1 Some Computer Essentials

Fig. 1.5 shows the essential elements of any computer system. As its very purpose for existence, a computer can perform arithmetic or logical calculations. It does this in a

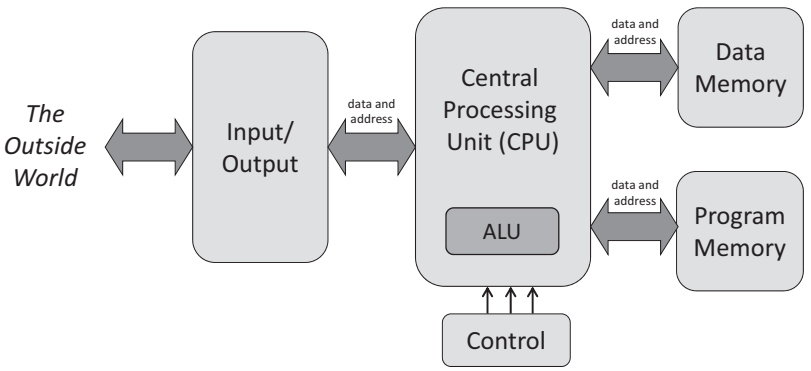

Figure 1.5
Essentials of a computer.