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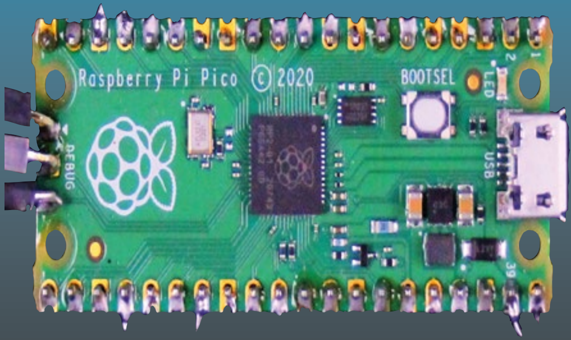

RP2040 Assembly Language Programming

ARM Cortex-M0+ on the Raspberry Pi Pico

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Stephen Smith

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Printed on acid-free paper

This book is dedicated to my beloved wife and editor Cathalynn Labonté-Smith.

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About the Author

Stephen Smith is also the author of the Apress titles *Raspberry Pi Assembly Language Programming and Programming with 64-Bit ARM Assembly Language*. He is a retired software architect, located in Gibsons, BC, Canada. He's been developing software since high school, or way too many years to record. He was the chief architect for the Sage 300 line of accounting products for 23 years. Since retiring, he has pursued artificial intelligence, earned his Advanced HAM Radio License, and enjoys mountain biking, hiking, and nature photography, and is a member of the Sunshine Coast Search and Rescue group. He continues to write his popular technology blog at `http://smist08.wordpress.com` and has written two science fiction novels in a series, Influence and Unification, available on `http://amazon.com`.

About the Technical Reviewer

Stewart Watkiss is a keen maker, programmer, and author of *Learn Electronics with Raspberry Pi*. He studied at the University of Hull, where he earned a master's degree in electronic engineering, and more recently at Georgia Institute of Technology, where he earned a master's degree in computer science.

Stewart also volunteers as a STEM ambassador, helping teach programming and physical computing to schoolchildren and at Raspberry Pi events. He has created a number of resources using Pygame Zero, which he makes available on his website (www.penguintutor.com).

Acknowledgments

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I want to thank all the good folk at Apress who made the whole process easy and enjoyable. A special shout-out to Jessica Vakili, my coordinating editor, who kept the whole project moving quickly and smoothly. Thanks to Aaron Black, senior editor, who recruited me and got the project started. Thanks to Stewart Watkiss, my technical reviewer, who helped make this a far better book.

Introduction

There is an explosion of DIY electronics projects, largely fueled by the Arduino-based microcontrollers and Raspberry Pi computers. Electronics projects have never been easier to build, with hundreds of inexpensive modular components to choose from. People are designing robots, home monitoring and security systems, game devices, musical instruments, audio systems, and a lot more. The Raspberry Pi Pico is the Raspberry Pi Foundation's entry into the Arduino-style microcontroller market. A regular Raspberry Pi computer runs Linux and typically costs from $35 to $100 depending on memory and accessories. The Raspberry Pi Pico costs $4 and doesn't run an operating system.

To power the Raspberry Pi Pico, the Raspberry Pi Foundation designed a custom system on a chip (SoC), called the RP2040, containing dual ARM Cortex-M0+ CPUs along with a raft of device controller components. This combination of a powerful CPU and ease of integration has made this a great choice for any DIY project. Further, Raspberry sells the RP2040 chips separately, and other companies such as Seeed Studio, Adafruit, and Pimoroni are selling their own versions of this microcontroller with extra built-in features like Bluetooth or Wi-Fi. You can even buy RP2040 chips yourself for $1 each and build your own board.

At the basic level, how are these microcontrollers programmed? What provides the magical foundation for all the great projects that people build on them? Raspberry provides an SDK for C programmers as well as support for programming in MicroPython. This book answers these questions and delves into how these are programmed at the bare metal level and provides insight into the RP2040's architecture.

Assembly Language is the native, lowest-level way to program a computer. Each processing chip has its own Assembly Language. This book covers programming the ARM Cortex-M0+ 32-bit processor. To learn how a computer works, learning Assembly language is a great way to get into the nitty-gritty details. The popularity and low cost of microcontrollers like the Raspberry Pi Pico provide ideal platforms to learn advanced concepts in computing.

Even though all these devices are low powered and compact, they're still sophisticated computers with a multicore processor, programmable I/O processors, and integrated hardware controllers. Anything learned about these devices is directly relevant to any gadget with an ARM processor, which by volume is the number one processor on the market today.

In this book, we cover how to program ARM Cortex-M0+ processors at the lowest level, operating as close to the hardware as possible. You will learn the following:

- How to format instructions and combine them into programs, as well as details of the operative binary data formats
- How to program the built-in programmable I/O, division, and interpolation coprocessors
- How to control the integrated hardware devices by reading and writing to the hardware control registers directly
- How to interact with the RP2040 SDK

The simplest way to learn these tasks is with a Raspberry Pi Pico connected to a Raspberry Pi running the Raspberry Pi OS, a version of Linux. This provides all the tools needed to learn Assembly Language programming. All the software required for this book is open source and readily available on the Raspberry Pi.

This book contains many working programs to play with, use as a starting point, or study. The only way to learn programming is by doing, so don't be afraid to experiment, as it is the only way to learn.

Even if Assembly programming isn't used in your day-to-day life, knowing how the processor works at the Assembly Language level and knowing the low-level binary data structures will make you a better programmer in all other areas. Knowing how the processor works will let you write more efficient C code and can even help with Python programming.

Enjoy your introduction to Assembly Language. Learning it for one processor family helps with learning and using any other processor architectures encountered throughout your career.

Source Code Location

The source code for the example code in the book is located on the Apress GitHub site at the following URL:

`https://github.com/Apress/RP2040-Assembly-Language-Programming`

The code is organized by chapter and includes answers to the programming exercises.

CHAPTER 1

How to Set Up the Development Environment

Microcontrollers like the Raspberry Pi Pico are typically utilized as the brains for smart devices, like microwave ovens, dishwashers, home security systems, weather stations, or irrigation monitors and controllers. At best, they have a small display and perhaps a couple of buttons for taking commands; however, they are still fully functioning computers. The programs that run on them can be quite powerful and sophisticated. Since the microcontroller usually doesn't have a keyboard, mouse, or monitor, we develop their programs on a regular computer, known as a host computer, and then upload the program to the microcontroller to test and finally deploy it.

The Raspberry Pi Pico is a board built around Raspberry's RP2040 ARM CPU chip. Not only is this the heart of the Raspberry Pi Pico, but also Raspberry sells this chip to other manufacturers, including Adafruit, Arduino, Seeed Studio, SparkFun, and Pimoroni. These other companies produce boards like the Raspberry Pi Pico but with different feature sets. For instance, some contain Wi-Fi or Bluetooth functions, easily connect to rechargeable batteries, or are in much smaller form factors. In this book, when we refer to the RP2040, it applies to all the brands of RP2040

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boards. However, in some cases, we will talk about a specific board, perhaps, because we are discussing Wi-Fi or are referring to specific wiring connections for one board.

Programming the RP2040 in Assembly Language is the main emphasis of this book, but we want to do this by studying real working programs. To do this, we need to hook up our microcontroller to various pieces of hardware. This way we can see programs that perform useful tasks and learn all the flexible and powerful features the RP2040 has to connect to external sensors, controllers, and communication channels. To begin with, we set up the Raspberry Pi Pico on an electronics breadboard, so we can easily wire in the various devices to play with.

This chapter is concerned with physically setting up the Raspberry Pi Pico on a breadboard and wiring it up to a host computer to effortlessly program and debug programs, as well as hook up other components as we encounter them. The *Getting started with Raspberry Pi Pico* guide (from `www.raspberrypi.org/documentation/rp2040/getting-started/`) is an excellent reference on how to do these fundamental tasks. We will not duplicate the contents of the guide; instead, we will point out the important parts that are required for Assembly Language programming, debugging, and playing with the sample programs in this book.

To run most of the programs in this book, you will need

- A Raspberry Pi Pico
- An electronics breadboard
- Pins to attach the Pico to the breadboard
- Miscellaneous connecting wires
- A selection of LEDs
- A soldering iron and solder
- A Raspberry Pi 4 running Raspberry Pi OS

About the Raspberry Pi Pico

The heart of the Raspberry Pi Pico is a new chip developed by Raspberry and ARM. This chip is a system on a chip (SoC) that contains a dual core ARM Cortex-M0+ CPU, 264KB of SRAM, USB port, and support for several hardware devices. Compared to a full computer like the regular Raspberry Pi, the Raspberry Pico lacks a video output port, an operating system, and USB ports for a keyboard and a mouse. But it is possible to connect displays and input devices to the Raspberry Pi Pico, as we'll see later in the book. The specialty connections and input devices aren't used for general-purpose computing; rather, they solve specific problems, such as powering a vending machine and monitoring a greenhouse.

Unlike the CPUs found in desktop and laptop computers, the RP2040 doesn't contain a floating-point unit, vector processing unit, or graphic processing unit. However, one thing it has that regular CPUs lack is a set of eight programmable I/O (PIO) coprocessors. These PIOs have their own Assembly Language and can handle many I/O protocols and tasks independent of the two CPU cores. We'll cover PIOs in Chapter 11. If you already have your RP2040 board wired up and know how to download and debug C programs, then you might want to skip ahead to Chapter 2.

The RP2040 may look underpowered when comparing it to a modern Intel, AMD, or ARM processor, but for the price, it is quite a powerful computer. Table 1-1 compares the RP2040 to some older and newer computers as well as competitors' microcontrollers.

Table 1-1. *Comparison of the Processing Power of the RP2040*

Computer	CPU	Speed (MHz)	Memory (KB)	Bits	Cores
Apple II	MOS 6502	1	48	8	1
IBM PC	Intel 8088	4.77	640	16	1
Arduino Nano	ATmega 328	16	2	8	1
Arduino Due	ARM M3	84	96	32	1
RP2040	**ARM M0+**	**133**	**264**	**32**	**2**
Pi Zero	ARM A53	1024	524,288	32	1
Pi 4	ARM A72	1536	8,388,608	64	4

About the Host Computer

Since microcontrollers don't have a keyboard, a display, or even an operating system, their programs are written on a host computer. For RP2040-based microcontrollers, this could be on a MacOS, Windows, or Linux-based computer. The Raspberry Pi Pico documentation has instructions on how to connect it to all these platforms. The easiest solution is to use a Raspberry Pi 4 as the host vs. using a Windows or Mac computer. Raspberry has made this easy with a complete installation script and clear instructions on how to wire the Raspberry Pi 4 and Raspberry Pi Pico together. The wiring solution of these two boards is the easiest one since the Raspberry Pi 4 already exposes all the necessary pins via its GPIO pins. In this book, we'll use the Raspberry Pi 4, point out the features we will be using, and let you follow the Raspberry-provided documentation to set it up.

How to Solder and Wire

You can't do much with a Raspberry Pi Pico without doing some soldering. Without soldering, you can download programs to the RP2040, flash the onboard LED, and send data back out the USB port to the host computer. However, even to just debug a program, you must do some soldering. The easiest way to set things up is to solder a set of pins to each side of the board, so it can be inserted into an electronics breadboard, which then allows us to connect things up without further soldering. This is great for experimenting. Typically, we would use a new RP2040 board to solder into a final project. At $4 each, there isn't a significant overhead in having a development board and adding new boards to the package when you are finished. To perform debugging requires you to solder pins to the three debugging connections on the end of the board.

The minimum wiring needed is the following three connections between the Pico and the Raspberry Pi 4:

1. Using a micro-USB cable
2. Via the three debugging pins
3. Via a serial port using pins 1, 2, and 3

Don't be scared of soldering; it is actually quite simple and fun. The main trick is to heat up the area where you want the solder to go and touch a bit of solder there. Don't melt it onto the soldering iron's tip and then try to drip it from there. Some vendors provide an option to purchase boards with the pins presoldered for a few dollars extra. Others provide the pins separately, and it is up to you to ensure they are included in your order. Even if the main pins are presoldered, chances are you are going to need to solder pins to the three debug pads. Figure 1-1 shows the wiring, minus the USB cable, of a Raspberry Pi Pico connected to a Raspberry Pi 4.

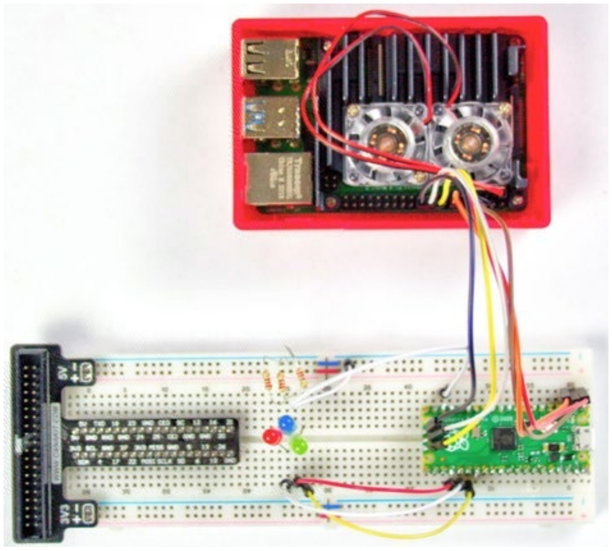

Figure 1-1. *A Raspberry Pi Pico installed in a breadboard and connected to a Raspberry Pi4. The USB cable was removed for clarity. Three LEDs are connected as well.*

Note If you are using an RP2040 board other than the Raspberry Pi Pico, then it is likely that the pins are in different locations on the board, and you will need to adapt the wiring for the location of the pins.

How to Install Software

If you are using a Raspberry Pi as your host computer, then this is straightforward. Use the Raspberry Pi OS as your operating system. This simplifies installation, since it runs 32-bit ARM code and shares development tools with the Raspberry Pi Pico and other RP2040-based boards. The pico_setup.sh script downloads and installs everything required to develop code for RP2040-based systems. As Raspberry's *Getting Started* guide documents, you get pico_setup.sh using wget:

```
wget https://raw.githubusercontent.com/raspberrypi/pico-setup/
master/pico_setup.sh
```

This script sets up both C and Assembly Language programming.

The *Getting Started* guide includes instructions for working with Visual Studio Code, which you are welcome to use, but we won't be covering in this book. This book covers text files that can be edited in any editor, using cmake and make for building, gdb and openocd for debugging, and the minicom for communications.

A Simple Program to Ensure Things Are Working

The easiest way to ensure everything is working is to compile and play with a couple of the SDK examples. The *Getting started with Raspberry Pi Pico* guide walks you through how to do this. Here, rather than duplicate, we'll list the key things you need to be comfortable with, since we will be doing them over and over throughout this book. Here is what you need to know:

1. How to load a program by powering on the Pico while holding down the BootSel button and copying a program to the shared drive
2. How to compile a program to either send its output to the USB or serial port
3. How to use the minicom to display the output that the Pico is sending

4. How to compile a program for debugging
5. How to use openocd and gdb to load and execute a program for debugging

---

Tip Building a program requires running both cmake and make. It isn't always clear which part does what. If you make configuration changes, it is best to delete and recreate the build folder ensuring everything is built from scratch.

Create Some Helper Script Files

When you follow along with the *Getting started with Raspberry Pi Pico* guide, there are quite a few long command lines to type in (or to copy/paste). It saves quite a bit of time to create a collection of small shell scripts to automate the common tasks. You can put these in $HOME/bin and then add

```
export PATH=$PATH:$HOME/bin
```

to the end of the $HOME/.bashrc file. You also need to make these executable with

```
chmod +x filename
```

Next, we need two scripts for minicom—one to listen on the UART and one to listen on the USB, as follows:

File m-uart:

```
minicom -b 115200 -o -D /dev/serial0
```

File m-usb:

```
minicom -b 115200 -o -D /dev/ttyACM0
```

To build debug, I have a script cmaked containing

```
cmake -DCMAKE_BUILD_TYPE=Debug ..
```

To run openocd, ready to accept connections from gdb, I have the script ocdg containing

```
openocd -f interface/raspberrypi-swd.cfg -f target/rp2040.cfg
```

To run gdb-multiarch where the elf file to be debugged is passed as a parameter, I have gdbm containing

```
gdb-multiarch $1
```

When gdb starts, we need to connect to openocd. We can automate this by creating a .gdbinit file in $HOME. This file then contains

```
target remote localhost:3333
```

Note This .gdbinit will be used anytime you start gdb, so if you need to debug a local file without using openocd, then you might want to rename this file while you do that.

Summary

This chapter is the starting point. We haven't done any Assembly Language programming yet, but now we are set up to write, debug, test, and deploy programs written in either C or Assembly Language. The Raspberry Pi Pico is connected to the Raspberry Pi 4 through a USB cable, a serial port, and the debugging port. The Pico is installed in an electronics breadboard ready to have other components connected to it. In Chapter 2, we will use all these tools to start our journey with RP2040 Assembly Language.

CHAPTER 2

Our First Assembly Language Program

Most of the functionality of a Raspberry Pi Pico is contained in the custom RP2040 chip that contains dual core ARM Cortex-M0+ CPUs. The ARM processor was originally developed by a group in Great Britain, who wanted to build a successor to the BBC Microcomputer used for educational purposes. The BBC Microcomputer used the 6502 processor, which was a simple processor with a simple instruction set. The problem was there was no successor to the 6502. They weren't happy with the microprocessors that were around at the time, since they were much more complicated than the 6502 and they didn't want to make another IBM PC clone. They took the bold move to design their own. They developed the Acorn computer that used it and tried to position it as the successor to the BBC Microcomputer. The idea was to use Reduced Instruction Set Computer (RISC) technology as opposed to Complex Instruction Set Computer (CISC) as championed by Intel and Motorola.

Developing silicon chips is an expensive proposition, and unless you can get a good volume going, manufacturing is expensive. The ARM processor probably wouldn't have gone anywhere except that Apple came calling looking for a processor for a new device they had under development—the iPod. The key selling point for Apple was that as the ARM processor was RISC, therefore, it used less silicon than CISC processors and as a result used far less power. This meant it was possible to build a device that ran for a long time on a single battery charge.

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Unlike Intel, ARM doesn't manufacture chips, it just licenses the designs for others to optimize and manufacture chips. With Apple onboard, suddenly there was a lot of interest in ARM, and several big manufacturers started producing chips. With the advent of smartphones, the ARM chip really took off and now is used in pretty much every phone and tablet and even powers some Chromebooks, making it the number one processor in the computer market.

The designers at ARM are ambitious and architect their processors ranging from low-cost microcontrollers all the way up to the most powerful CPUs used in supercomputers. ARM's line of microcontroller CPUs is the Cortex-M series. We are most interested in the ARM Cortex-M0+ used in Raspberry's RP2040 SoC. To make this chip inexpensive, the transistor count is reduced as much as possible. The M-series CPUs are all 32 bits but have fewer registers and a smaller instruction set than the full A-series ARM CPUs like those used in the full Raspberry Pi. The M-series CPUs are optimized to use as little memory as possible as memory tends to be limited in microcontrollers, again to keep costs down. In this book, we'll see how the Cortex-M0+ works at the lowest level and will often have to deal with the trade-offs made by the chip designers keeping transistor counts down. There are several optional components available from ARM for these chips. We'll consider the ones included in the RP2040, such as the fast integer multiplier and divider (multiplication and division are an extra).

10 Reasons to Use Assembly Language

You can program the Raspberry Pi Pico in MicroPython or C/C++. These are productive languages that hide the details of all the bits and bytes, letting you focus on your application problem. When you program in Assembly Language, you are tightly coupled to a given CPU, and moving your program to another CPU requires a complete rewrite. Each Assembly