RustyGecko - Developing Rust on Bare-Metal

An experimental embedded software platform

Håvard Wormdal Høiby
Sondre Lefsaker

Master of Science in Computer Science

Submission date:	June 2015
Supervisor:	Magnus Lie Hetland, IDI
Co-supervisor:	Antonio Garcia Guirado, IDI
	Marius Grannæs, Silicon Labs

Norwegian University of Science and Technology
Department of Computer and Information Science

Preface

This report is submitted to the Norwegian University of Science and Technology in fulfillment of the requirements for master thesis.

This work has been performed at the Department of Computer and Information Science, NTNU, with Prof. Magnus Lie Hetland as the supervisor, Antonio Garcia Guirado (ARM), and Marius Grannæs (Silicon Labs) as co-supervisors. The initial problem description was our own proposal and further developed in co-operation with our supervisors.

Acknowledgements

Thanks to Magnus Lie Hetland, Antonio Garcia Guirado, and Marius Grannæs for directions and guidance on technical issues and this report. Thanks to Silicon Labs for providing us with development platforms for us to develop and test our implementation on. Thanks to Antonio Garcia Guirado for the implementation of the `CircleGame` application for us to port to Rust and use in our benchmarks. Thanks to Itera w/Tommy Ryen for office space. A special thanks to Leslie Ho and Siri Aagedal for all the support and for proofreading the thesis.

Sondre Lefsaker and Håvard Wormdal Høiby 2015-06-14

Project Description

The Rust programming language is a new system language developed by Mozilla. With the language being statically compiled and built on the LLVM compiler infrastructure, and because of features like low-level control and zero-cost abstractions, the language is a candidate for use in bare-metal systems.

The EFM32 series of microcontrollers focuses on energy efficiency and for their ability to function in power constrained environments. The tool suite by the vendor, Silicon Labs, includes energy monitoring tools to analyze energy consumption at the source code level. The series is based on the ARM Cortex-M processor family. With ARM's move towards using LLVM in their own toolchain, a back-end for the Cortex-M series is already available.

The goal of the project is to explore programming for the EFM32 series of microprocessors with the Rust Programming Language. This should be realized by using as much of the features and tools available in the Rust ecosystem as deemed fit. This whole platform should be evaluated and compared to the existing C platform provided by Silicon Labs.

Abstract

Embedded computer systems are an invisible, ever-growing part of our lives. Through market trends, like the *Internet of Things*, these computers are brought to new domains. These constrained systems set different requirements to the tools used to develop software, compared to the conventional systems found in mobile, desktop, and server computers.

In recent decades, the number of programming languages have flourished on conventional computer systems. The traditional categorization of *high-level languages* have shifted from static and hardware platform-agnostic languages like C, to the dynamic and highly managed languages like JavaScript. The safety mechanisms provided by these new high-level languages come at a cost of the low-level control found in *low-level languages.*

Rust is an emerging programming language that has a new take on this trade-off between control and safety. This language takes a static approach for guaranteeing the safety, which a high-level language needs to ensure with dynamic checking.

In this thesis, we present our experiments and evaluate the result of bringing Rust to a bare-metal computer system. We describe the design and implementation of our *bare-metal* platform called `RustyGecko`, which encompasses libraries for controlling the hardware device. On this platform, we developed and evaluated several programs and abstract libraries.

To support our platform, we have developed and presented an extension to the Rust standard package manager, which facilitates building Rust applications for non-standard targets. The extension was ultimately contributed back to the package manager project.

We have evaluated the platform based on performance, energy consumption, and code size. These results were compared to the existing C platform for the target chip, the ARM Cortex-M3 based EFM32GG called Giant Gecko. Our evaluation shows that Rust performs equally well when considering performance and energy consumption. However, we find that the code size can increase substantially, especially when building the applications in debugging mode.

Sammendrag

Innvevde datasystemer blir gradvis en større del av vår hverdag. Disse datamaskinene må stadig tilpasse seg nye domener, slik som *tingenes internett*. Sammenlignet med andre konvensjonelle datasystemer (mobile-, personlige-, og tjenestesystemer), er mange begrensninger i disse systemene som setter krav til hvilke utviklingsverktøy som kan brukes.

I nyere tid har det kommet mange nye programmeringsspråk som er tilrettelagt for konvensjonelle datasystemer. Kategoriseringen av *høyere-nivå programmeringsspråk* har endret seg i løpet av de siste tiårene, fra å handle om statiske, maskinvare-agnostiske språk som C, til å dreie seg om dynamiske språk med kjøretidssytemer, slik som JavaScript. Sikkerhetsmekanismene som er tilgjengelige i disse høyere-nivå språkene kommer ofte på bekostning av lav-nivå kontroll, som er tilgjengelig i *lav-nivå programmeringsspråk*.

Rust er et nytt og voksende programmeringsspråk, som gjør et forsøk på å skape et nytt kompromiss mellom kontroll og sikkerhet. Dette språket kan garantere sikkerhet ved statisk analyse, som i andre høyere-nivå språk blir løst dynamisk.

I denne avhandlingen presenterer vi vår metode for å benytte Rust i et innvevd datasystem, og en evaluering av denne. Vi beskriver designet og implementasjonen av vår operativsystemløse plattform kalt `RustyGecko`, som omfatter biblioteker for å kontrollere maskinvaren. Vi vister i tilleg flere programmer og abstrakte biblioteker som er blitt bygget på denne plattformen.

For å støtte plattformen har vi også implementert og presentert en utvidelse til Rust sin standard pakkebehandler. Denne utvidelsen gjør det enklere å bygge Rust-applikasjoner for ikke-standard plattformer, og har også blitt inkludert i det opprinnelige prosjektet som utvikler pakkebehandleren.

Vi har evaluert plattformen basert på ytelse, energieffektivitet og kodestørrelse, ved bruk av en ARM Cortex-M3-basert EFM32-brikke kalt Giant Gecko. Disse resultatene har blitt sammenlignet med den allerede eksisterende C plattformen. Våre evalueringer viser at Rust har tilsvarende ytelse og energieffektivitet som C. Vi har imidlertid oppdaget at kodestørrelsen kan øke betraktelig, særlig for applikasjoner som er bygget for feilsøking.

Contents

List of Tables

List of Figures

List of listings

List of Abbreviations

ABI Application Binary Interface. 2, 45, 47, 63, 65, 82, 119

ACMP Analog Comparator. 60

ADC Analog to Digital Converter. xvii, xviii, 37, 38, 54–58, 60, 67, 86, 87, 90, 93, 94, 97

API Application Program Interface. 38, 58, 63, 73, 76, 81, 94, 127, 130

CLI Command Line Interface. 91, 98

CMSIS Cortex Microcontroller Software Interface Standard. 38, 39, 58, 59, 129

CMU Clock Management Unit. 60

CPU Central Processing Unit. 3, 33, 37, 38, 41, 42, 59, 60, 92, 93, 99

CSE Common Subexpression Elimination. 84

CUT Code Under Test. 68

DAC Digital to Analog Converter. 37, 38, 93

DCE Dead Code Elimination. 114

DMA Direct Memory Access. xviii, 36–38, 60, 62, 93, 94

EBI External Bus Interface. 60

EMU Energy Management Unit. 60

FFI Foreign Function Interface. xviii, 27, 28, 55, 58, 64–68, 73, 74, 122

FPS Frames per Second. xv, 99–101, 103–105, 124

GPIO General Purpose Input/Output. xviii, 37, 39, 40, 60, 82, 91–93

HAL Hardware Abstraction Layer. 37, 38

I^{2}C Inter-Integrated Circuit Interface. 36, 59, 60, 62, 97

IoT Internet of Things. v, 1, 3, 33

IRQ Interrupt Request. 59

ITM Instrumentation Trace Macrocell. 38

LCD Liquid-crystal Display. 34, 60, 99, 100

LESENSE Low Energy Sensor Interface. 60

LEUART Low Energy Universal Asynchronous Receiver/Transmitter. 60

LTO Link Time Optimization. 65, 112

MCU Microcontroller Unit. xvii, 3, 5, 6, 8, 11, 32, 34, 36, 37, 39, 40, 42–44, 47, 53, 63, 72, 77, 81, 91, 92, 117, 120, 121

MMIO Memory Mapped I/O. xviii, 54–58, 120, 122

NVIC Nested Vector Interrupt Controller. 38, 59, 63

OS Operating System. 3, 8, 14, 51, 118

RAM Random Access Memory. 8, 42, 54, 86, 94, 96, 97

RCL Rust Core Library. xiii, 14, 15, 39, 49, 50, 72, 73, 118

REL Rust Embedded Library. 6, 49, 51, 71, 74, 79, 81, 115, 118, 120, 129

REM Rust Embedded Modules. xviii, 91–93

RNG Random Number Generator. 104, 116

ROM Read Only Memory. 41

RSL Rust Standard Library. 14, 44, 45, 50, 51, 79, 117–119, 127

RTC Real Time Counter. xvii, 37, 38, 60, 97

UART Universal Asynchronous Receiver/Transmitter. 36, 37, 59, 60

USART Universal Synchronous Asynchronous Receiver/Transmitter. xviii, 36, 37, 60, 61, 67, 68, 91–93, 96, 98, 121

Chapter 1

Introduction

Embedded computer systems constitute a vast majority of the computers we use today. These systems are not as visible as desktop and laptop systems, and they have different requirements when it comes to their programmers and the languages they use. Applications written for these computers control the hardware more directly, thus, the language requires low-level control. Modern compiler infrastructures have made great advances in recent years. These advances enable high-level abstraction to avoid coming at the cost of not providing the low-level control needed in these applications. The `Rust` programming language is one example of a language built on such an infrastructure, and it targets this combination of abstractions and low-level control. In the years to come, many of these computer systems will be connected to the Internet to facilitate the Internet of Things. This development will expose more programmers to embedded systems. Introducing `Rust` to these systems is potentially beneficial if applications can be developed with higher programmer productivity.

1.1 Motivation

`Rust` is a new programming language that reached a stable 1.0 in May 2015. Like most programming languages, it aims to solve a few specific problems better than other languages. Mainly, its goal is "to design and implement a safe, concurrent, practical, static systems language" [8]. With these goals in mind, `Rust` focuses on being a memory safe language without sacrificing performance. The language implements a few paradigms to provide a solid concurrency model that is suited for many modern applications that run on the Internet.

`C` has become the industry standard for developing on embedded systems. It is a small, low-level language, at least considering today's standards, that has been adapted to virtually every target platform that exists on the market. It is an easy language without many language constructs, which makes it easy to adapt to different platforms. It also has a minimal runtime system and does not require an operating system to utilize the underlying hardware. `Rust` has adapted many of the features that are available in `C`. Among them are a minimal runtime, full control over the memory and an opt-in Application Binary Interface (ABI), which is exactly the same as `C`'s [5].

Gradually, while the `Rust` programming language started to take shape, a few people in the community took notice to `Rust`'s low level of implementation and how it could be a suitable programming language for embedded systems. Combined with its strong guarantees about memory safety, absence of data races, and other common errors like stack- and buffer-overflows, it makes for an interesting language to run on embedded systems. Early projects that experimented with running `Rust` bare-metal on ARM microcontrollers had to do a few workarounds in order to make it work. As the language is implemented in the open, with great influence from the community, it is now easy to rely on only the core functionality of the language that is platform independent.

The purpose of this project has been to try and give a rough comparison of `Rust` and `C` on a bare-metal system. In the process of doing this, we decided that the EFM32 microcontrollers from Silicon Labs would be well suited for the task. This platform gives us a couple of metrics where we can compare the two languages. Mainly, we want to compare the performance of the two languages against each other on a small system with limited computing power. In addition, we want to compare energy consumption of programs written in the two languages. Typically, the two problems go hand-in-hand, and the best way to save power is to shut down the hardware. In order to shut down the processor, the programs need to finish quickly - basically, executing as few instructions as possible. `Rust` claims to provide zero-cost abstractions, meaning that its high-level abstractions do not come at the cost of performance and program overhead. This claim is especially important to verify in an embedded system where excess resources are limited.

1.2 Embedded Computer System

An *embedded computer system* is a special purpose computer system where the computer is *embedded* in the device it controls. These computers are much smaller than a conventional server, desktop, and laptop computer, but are by far more numerous. A regular household contains embedded systems in devices like microwave ovens, dishwashers, and alarm systems. In a car, one finds embedded computers that are controlling the brakes of the car, the automatic windows, and navigation and entertainment systems.

In recent years, a trend of devices called wearables are emerging, which also has an embedded computer at its core. The Internet is growing, and according to Gartner [2] the number of connected devices will increase from ∼5 billion in 2015 to ∼25 billion by 2020. A vast majority of this increase is due to the embedded computer systems known as the Internet of Things (IoT) [27].

1.2.1 Abstraction Level

In most computer systems, the hardware interaction and resource management is abstracted away with an Operating System (OS). This abstraction layer makes it possible for the programmers of these systems to write portable programs built with higher level languages. The added overheads of using a high-level language are small enough compared to the added productivity and convenience for the programmer. Some embedded systems are also based on an OS, projects like Raspberry PI[1] and Tessel[2] employs reduced Linux versions to run Python and JavaScript respectively.

In some embedded systems, these complexities that lead to lower performance and higher memory usage, makes it hard to benefit from an OS. With the absence of an OS, applications for embedded system are usually written in a lower level languages. These languages must provide the low-level control that is needed by the programmer to interact directly with the hardware. A well-known project running without an OS is the electronic prototyping platform Arduino[3]. The EFM32 `emlib` library used in this thesis is also a platform for `C` programming without an OS.

In this thesis we use *bare-metal* to refer to execution of code directly on the hardware, without the abstraction of an OS. This is the only execution mode that we have targeted in this project.

1.2.2 Programming Model

A common programming model used in embedded systems is the *Event-driven* programming model. In this model, the program is controlled by events which triggers actions to be executed. Within an embedded system, these events are *hardware interrupts*, and the actions are *handler functions.* A typical example of this event-action pair is the interrupt that is issued by pressing a button and the action of turning on a LED.

Other events that trigger interrupt handlers to be executed in an embedded system is timers, sensors with available data, and communication peripherals ready to receive or send data. This programming model is successful in these systems because the peripherals controlled by the MCU usually requires time to perform its operation. The asynchronous nature of the model lets the Central Processing

[1]`https://www.raspberrypi.org/`
[2]`https://tessel.io/`
[3]`http://www.arduino.cc/`

Unit (CPU) avoid the busy-waits that are implied when using a more synchronous model.

1.2.3 Programming Language

Lower-level languages have usually been the preferred ones for programming of embedded systems. Traditionally, a large portion of code bases consists of `C`, `Assembly`, and `C++`. Figure 1.1 shows a VDC Research [10] survey over languages used in embedded systems. According to the survey, the usage of `C` and `assembly` are on the way down in favor of higher level languages like `C++`, `Java`, and `C#`.

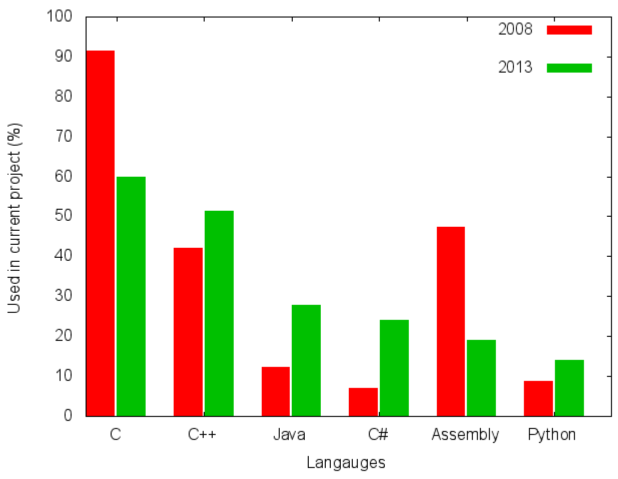


Figure 1.1: Survey of language used on current embedded system project by VDC Research

The runtime system for *managed* languages like `Java`, `Python`, and `C#`, features automatic memory management. This memory management lets the language ensure memory safety, but incurs a runtime cost and can make performance analysis non-deterministic. When these languages are used for bare-metal programming, the memory management is usually altered [24] [13] [4].

1.3 Benefits of the Rust language

The `Rust` programming language implements a novel approach to *memory management* based on region based memory management from `Cyclone` [14, 26]. This

[4]`http://en.wikipedia.org/wiki/.NET_Micro_Framework`

kind of memory management substitutes the runtime checks, performed by an automatic memory manager, with static analysis performed by the compiler [12]. This approach lets the `Rust` language ensure memory safety without the runtime cost of automatic memory management.

One of the design goals for `Rust` is to provide *Zero-Cost Abstractions*. One implication of this goal is that abstractions in `Rust` should not have worse performance than the same, less abstracted, code in other low-level languages. This design goal makes the language a good fit for embedded systems as costly abstractions could have rendered parts of the language useless.

`Rust` has a distinction between *safe* and *unsafe* code. For this, `Rust` provides a concept of `unsafe` sections where the compiler relies on the programmer to ensure that the safe invariants are maintained. This section can be used when building abstractions in `Rust`, as the compilers rules for ensuring safety can sometimes become too strict. Containing these sections in `unsafe` sections makes it easier for the programmer to reason about the safety of the code.

The `Rust` language is developed by the Mozilla Foundation. With this foundation, comes a range of *Open Source* projects and a vibrant community. This makes the community around `Rust` an open and inviting space for sharing knowledge and code. The `Rust` language and compiler is developed in the open, on the GitHub[5] code collaboration platform. The openness makes for a low entry cost both in learning from the project and contributing to it. Throughout the work for this thesis, we have both had a huge benefit of the openness of the development, and had the chance to contribute code back to the `Rust` project.

One particularly good tool for sharing and building `Rust` projects is the `Cargo` package manager. This tool makes sharing and reusing libraries of code very easy.

1.4 The RustyGecko Platform

In this thesis, we develop and evaluate the `RustyGecko`[6] platform, a bare-metal platform for `Rust` on the EFM32 series of MCUs. The platform is described by Figure 1.2. The blue colored sections describe the `Rust` modules that were developed or fitted for the platform, and the brown yellow sections show the base `C` libraries that the platform utilizes. The red section denotes the build system.

[5]`https://github.com/`
[6]`https://github.com/RustyGecko/`

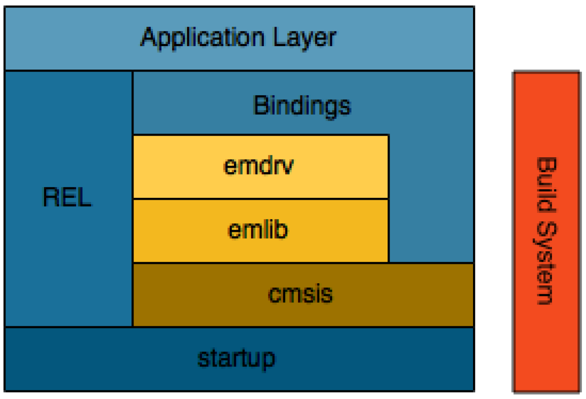


Figure 1.2: The contents of the RustyGecko platform

Figure 1.2 is described in a bottom-up perspective throughout Chapter 3 to Chapter 6 of this thesis. The `startup` module deals with the minimal requirements for booting a `Rust` application on the MCU and is described in Section 3.1. In Section 4.4, we define Rust Embedded Library (REL), the subset of the `Rust` standard library that is applicable for bare-metal systems.

In the center part of the figure, we find the peripheral libraries for controlling both the MCU and its connected devices, and these are used in `Rust` through language bindings. The details of these libraries and implementations are given in Section 5.2. In Chapter 6, we take a detour and look at the building system used to support development on the `RustyGecko` platform. Lastly, we consider some high-level libraries and applications that we place in the Application Layer platform.

The `RustyGecko` platform as a whole aims to bring the safety and high-level abstractions of `Rust` to bare-metal computer systems.

1.5 Interpretation of Assignment

In Table 1.1 we presented our interpretation of the Project Description. From these requirements, we chose to design and implemented the `RustyGecko` platform and measure applications written for it.

Requirement	Description
R1	Identify and describe the requirements for a bare-metal platform in `Rust`
R2	Prototype a bare-metal software platform for `Rust` on the EFM32
R3	Evaluate code size, performance and energy consumption

Table 1.1: Requirements from Project Description

Challenges related to **R1** was identified in a *Kickoff* meeting with Silicon Labs and are given in Table 1.2. These challenges are important to consider to provide a bare-metal platform in Rust.

Language Challenge	Description
LC1	Volatile read and write
LC2	Handling interrupts
LC3	Reading and writing hardware registers
LC4	Static object construction
LC5	Heap allocation
LC6	Error handling without allocation

Table 1.2: Language challenges in providing a bare-metal platform in `Rust`

In a regular program, the values of variables do not change without the program directly modifying the values. Compilers exploit this assumption and might remove redundant access to the same variables to improve performance. In multi-threaded code with global mutable state, this assumption does not hold. Access to these variables must be marked as *volatile* (**LC1**) to ensure the compiler genereates code to reread the value in case it was updated.

To program efficiently, both when it comes to performance and energy, embedded system makes extensive use of interrupts (**LC2**). These interrupts must execute quickly and will require support in the language.

In an embedded system, like the one considered in this thesis, a given portion of the memory space is used to represent hardware registers. The language needs a facility to read and write these registers (**LC3**).

Some languages allow object construction of statically allocated objects (**LC4**). These objects are constructed before the main entry point of the application. Thus, errors that occur while constructing these objects are challenging to handle.

Allocation of heap memory is a convenient mechanism for creating data structures with dynamic size. In an embedded system with no excess memory, the performance of heap allocation, with respect to the reuse of deallocated memory, is an important challenge (**LC5**).

On a system with an OS and large memory hierarchy, a technique called swapping can be used when the number of heap allocations exceed the capacity of the Random Access Memory (RAM) storage. In an embedded system, these facilities do not exist. When the application is out of memory, there is no way to allocate more. A subtle problem identified here is that when the error has occurred, the mechanism handling this condition cannot allocate memory, as this will also fail and trigger the mechanism in an infinite loop (**LC6**).

These language challenges are revisited as a part of the discussion of our platform in Section 9.1.3.

1.6 Project Outline

In this section, we break down the project into five phases. Table 1.3 presents each of the phases with their primary goals, and the rest of this section will describe how each phase was carried out, in more detail. In addition to the main phases of the project, the build system has evolved continuously.

Phase	**Goal**	**Finished**
Hello World	Blink LED with `Rust`	2015-01-09
Platform Design	Implement support libraries	2015-03-13
Development	Develop projects for measurements	2015-04-09
Measurement	Measuring the projects	2015-05-20
Evaluation	Evaluating the platform	2015-06-08

Table 1.3: Phases of the project

1.6.1 Phase 1 - Hello World

The initial phase of the project defined two main activities. Firstly, the direction of the project along with some major challenges was identified in a meeting with Marius Grannæs and Mikael Berg from Silicon Labs. Secondly, the milestone of running the first `Rust` application on the MCU was reached.

1.6.2 Phase 2 - Platform Design

After the initial compilation process was in place, the focus shifted towards developing the platform for writing larger applications. Throughout this phase, we developed the support libraries for the MCU, which are described in Section 4.4 and Section 5.2. Early in this phase, technical challenges guided the choice of which part of the platform to develop. The platform evolved continuously during the development phase.

1.6.3 Phase 3 - Development

The goal of the development phase was to create applications that would provide enough empirical data to evaluate the platform in phase 4. The two complementary projects in Table 1.4 were specified and implemented as part of this phase.

	Name	**Emphasis**
Project I	`SensorTracker`	Energy Efficiency
Project II	`CircleGame`	Performance

Table 1.4: Projects developed in development phase

Both of these projects were implemented in `Rust`, using the platform developed for this thesis, and in `C`, using the libraries provided by Silicon Labs.

1.6.4 Phase 4 - Measurement

During the measurement phase, the platform was evaluated based on the following metrics:

- Performance
- Energy Consumption
- Code Size

The results of the evaluation are presented and compared with the existing `C` platform in Chapter 8.

1.6.5 Phase 5 - Evaluation

Throughout this phase, we investigated the results that were gathered in the previous phase. These results provided a basis for a discussion of the project as a whole, which is presented in Chapter 9. In this discussion, we look at the viability of using `Rust` in a bare-metal system and present the thoughts we had, and the experiences we made, during the work for this thesis.

1.7 Contributions

The contributions of this thesis are given in Table 1.5.

Contribution	Description
C1	The `RustyGecko` platform
C2	Build process
C3	The `Cargo rustc` Subcommand
C4	Methods for using `Rust` abstractions
C5	Minor bugfix in a Silicon Labs library
C6	Evaluation of `Rust` for a bare-metal system
C7	Identifying binaries sizes as a problem

Table 1.5: Contributions of the Thesis

The design and implementation of the `RustyGecko` platform (**C1**), in addition to examples for using the platform.

The implemented build process (**C2**) is, to our knowledge, the first standard build process using the `Rust` package manager, `Cargo`, for bare-metal systems. Other projects have resorted to custom Makefiles to handle the build process and dependencies.

In order to develop the build process (**C2**), `Cargo` had to be modified. This resulted in implementing and contributing the subcommand (**C3**) to the `Cargo` package manager.

Throughout the development phase of the project, the high-level abstractions of `Rust` were tested out in a bare-metal environment. These experimentations resulted in a few successful and promising patterns (**C4**).

By porting a driver in one of Silicon Labs' software libraries from `C` to `Rust`, a minor bug was found and reported with a suggested patch (**C5**) to fix the issue.

The results reported and discussed in this thesis provides an evaluation (**C6**) of the `Rust` platform in a bare-metal system.

Considering the evaluation (**C6**), we have identified the size of the binaries produced by `Rust` are large for debugging a highly resource constrained embedded system (**C7**).

1.8 Report Outline

Chapter 1 Introduction introduces and gives motivation for using `Rust` in a bare-metal system. The interpretation of the assignment and an outline of the project is presented along with a summary of the contributions of the project.

Chapter 2 Background provides background material for the rest of the thesis. The Rust programming language is introduced along with the bundled package manager, `Cargo`. Further, the existing hardware platform, EFM32, and software libraries used for developing bare-metal applications are presented.

Chapter 3 Startup for Rust presents what happens in order for a `Rust` program to start executing on the MCU.

Chapter 4 Rust Embedded Library gives an overview over the `Rust` standard library for bare-metal systems.

Chapter 5 Binding Libraries goes into detail on the bindings developed for the peripheral libraries used to control the MCU.

Chapter 6 Build System looks at the build system used to build application for the `RustyGecko` platform.

Chapter 7 Application Layer present some high level libraries and some application build on the core `RustyGecko` functionality.

Chapter 8 Results present how the platform was evaluated and the results from the evaluation. The platform was evaluated by considering *code size*, *performance* and *energy efficiency*.

Chapter 9 Discussion provides a discussion of the platform and the results presented in Chapter 8.

Chapter 10 Conclusion presents a conclusion based on the discussion of the platform and outlines possible extensions and suggests further work based on this project.

Chapter 2

Background

This section contains all the background information that is deemed necessary in order to understand the content of the next chapters. We start by presenting the `Rust` programming language and some of its more prominent features, as well as the most important goals of the language. We assume that the reader is familiar with common programming languages like `Java`, `C`, and `C++` in order to understand some of the fundamental differences with memory management between these languages and `Rust`. After presenting `Rust`, we move on to the hardware and microcontrollers that we have used in this project, including their software suite called `emlib`.

2.1 The Rust Programming Language

`Rust`[1] is a new open source systems programming language developed with backing from the Mozilla Foundation[2]. It is a strongly and statically typed, multi-paradigm programming language that incorporates features from the functional, object-oriented, and imperative paradigms. The language borrows many constructs and features from other programming languages, some of which are described in the following sections. Over the course of `Rust`'s development, the language has set out to solve two major problems concerning both safety and concurrency, as well as taking full utilization of the underlying hardware.

2.1.1 Hello World

In Listing 2.1 we see the canonical 'Hello World' program implemented in `Rust`. We see that in `Rust` the program entry point is the `main` function which is defined in the top level scope of the application. The body of the function contains an

[1] `http://www.rust-lang.org/`
[2] `https://www.mozilla.org/en-US/foundation/`

invocation of the `println!` macro[3]. This macro has similar functionality to the `C` `printf` function, but verifies the usage of the function at compile time.

```rust
fn main() {
  println!("Hello, World!");
}
```

Listing 2.1: Hello World written in `Rust`

2.1.2 Language Features

This section starts by describing `Rust`'s standard library and its type-system, before moving on to presenting some of the language features that make `Rust` so different from `C`. Because `Rust` is a multi-paradigm language it offers a wider range of language constructs that are not present in the procedural paradigm usually found in embedded programming.

The Rust Standard Library

The Rust Standard Library (RSL) is included into all `Rust` programs and is an abstraction layer to write portable applications. The library consists of a collection of OS dependent implementations and a facade. The facede provides a thin wrapper which reexports a stable interface for libraries like `alloc` (for memory allocation), `collections` (general purpose data structures), and `core` (described in the next section). These OS dependent implementations renders the RSL unusable in a bare-metal system, as this dependency will not be met. It is, however, possible to opt-out of using the library.

It is important to note that there is a distinction between the actual software component called `std`, and the library we refer to as RSL. The RSL encompasses the standard library as a whole, i.e. `alloc` is a part of RSL. On the other hand, `std` is just the actual software component, i.e. `alloc` is not a part of `std`, even though it is reexported by `std`.

The Rust Core Library

RCL defines the platform independent part of the language. This library is not intended to be directly interfaced with by the application programmer; instead a stable interface is reexported through RSL. In this way, RCL is not interfaced with directly in normal `Rust` programs. This gives the developer the ability to modify the library while the RSL interface stays the same.

[3]Macros are distigiushed from functions by the leading `!` symbol.

Table 2.1 lists the primitive datatypes available in `Rust`. RCL defines many functions and abstractions that are used to manage and manipulate these datatypes. The table shows that `Rust` is explicit about the size and signedness of integer data types, and that in addition to the Pointer/Array distinction made by `C`, `Rust` also provides *slices*, *strings* and *tuples*.

Type	**Description**
`bool`	Either `true` or `false`
`char`	A UTF-8 scalar value
`f32`, `f64`	Floating point number of single and double precision
`u8`, `u16`, `u32`, `u64`	Unsigned integers
`i8`, `i16`, `i32`, `i64`	Signed integers
`isize`, `usize`	‘Pointer-sized’ Integers
Pointer	Raw unsafe[4] pointers (`*const T`, `*mut T`)
Array	Fixed-length array type, denoted with `[T]`
`slice`	A view into a array, denoted with `&[T]`
`str`	UTF-8 encoded byte array
Tuple	Finite ordered list of elements

Table 2.1: `Rust`’s primitive datatypes

Variables and Bindings

`Rust` features a handful of different data types, all of which can be assigned to a *variable* using a *binding*. The most important types are described in the following sections, but we will first look at how variables work. A value gets bound to a variable by utilizing the `let` keyword. A variable in `Rust` has a name and a value, much like other programming languages, but there is a distinct difference between the *mutability* of those variables.

With a mutable variable binding, it is possible to change the value of the variable. However, if we try to alter the value of an immutable variable binding, `Rust` will give us a compile-time error. The example code in Listing 2.2 shows how to declare both mutable and immutable variables and how to modify their values. The example will not work because we attempt to change the value of an immutable variable.

```rust
// bind the value ‘5’ to the immutable variable ‘a’
let a: i32 = 5;
// bind the value ‘10’ to the mutable variable ‘b’
let mut b = 10;
b = a; // change the value of ‘b’
a = b; // <- compiler error: re-assignment of immutable variable ‘a’
```

Listing 2.2: Variable bindings

An important part of variable bindings is `Rust`'s ability to automatically infer the data type of the variables. We can see from the example that `a` is defined as a 32-bit integer with the value 5, and because the variable `b` later gets assigned to `a`'s value, `Rust` will automatically infer `b` to be of the same type.

Enums

An `enum` in `Rust` (otherwise known as a sum type, or a tagged union, from type theory), is a data structure that is used to hold only one out of a small set of possible values. `Rust`'s `enum` construct is a class of *algebraic data types* that are common in functional programming languages, which means that its actual type is formed by combining other types together. This makes the `enum` a powerful feature of the language that can be used to deterministically limit the set of possible outcomes for a type. Listing 2.3 shows the definition of `Option`, taken from the standard library. This type is one of `Rust`'s most commonly used types and is used extensively throughout its standard library and other third party libraries and applications.

```rust
pub enum Option<T> {
  Some(T),
  None,
}
```

Listing 2.3: Definition of Option

Every `Option` variable is an `enum` that can either have the algebraic value `Some` or the *named value* `None`. If the variable is `Some`, the definition also says that it needs to contain a value of type `T`. This `T` can be anything and is how `Rust` defines a generic type. The `Option` type *can* be used to encode the same programming pattern as *pointers with a sentinel value of 0* (e.g. 0 for representing no value or the end of a datastructure), but in a fundamentaly safer way. The *null-pointer dereference* problem caused by using this pattern is called the *billion dollar bug* by its inventor Tony Hoare. For this reason, *safe* `Rust` does not allow for them to be used at all. In order to use a potential pointer which is contained within a `Option`, the programmer *must* unwrap the value and explicitly handle the case when the `Option` holds the value `None`. If it holds the value `Some`, the programmer is guaranteed by `Rust`'s memory safety guarantees, discussed later in this section, that the pointer is valid and safe to use. Even though the `Option` can be used analogous to a `C` pointer, it is important to note their differences. It acts more like a wrapper around a potential value, where its internal value is not *directly* accessible, which forces the programmer to handle the cases where it can be `None`. The usage of `enum` types described in this section become very expressive in combination with `match` expressions, as discussed in Section 2.1.2.

Structs

A `struct` in `Rust` is similar to that of `C` and is a way of creating more advanced data types than primitives or enums. With a `struct`, it is possible to combine multiple variables into a single type, each of them identified by its name. An example of defining a `Book` is shown in Listing 2.4. Anyone that is familiar with `C` will see the similarity of the `struct` definition, but there is also a couple of extra things to notice from the example. Everything in `Rust` is *private* by default, but the `pub` keywords on type definitions and member fields make them *publicly accessible*. The `impl` keyword allows us to implement member functions for the `Book`, similar to class-declarations in `C++` and other object-oriented languages.

```rust
pub struct Book {
  pub name: String,
  pub pages: u32,
}

impl Book {
  pub fn info(&self) {
    println!("{} has {} pages.", self.name, self.pages);
  }
}
```

Listing 2.4: Struct definition and implementation

Pointers

`Rust`'s `core` library exposes two pointer types that are considered *unsafe* by the language, which Section 2.1.7 explains. Pointers in `Rust` are a fundamental part of the language, but they are not used much outside of low-level code and bindings. Instead, the library offers higher-level structures as an abstraction between the *raw* pointers and their data.

Slices

The `Slice` type is simply a view into an array, and it is represented by a pointer and a length, as shown in Listing 2.5. `Slices` like the arrays comes with bounds checking, although this can be circumvented for performance reasons. The length is used to determine how many elements the slice represents. Note that the representation given here is internal to the compiler and the length property is not directly accessible. Slice syntax is denoted by `&[T]`, which reads like 'a slice of a finite array with type `T`.'

```
pub struct Slice<T> {
  pub data: *const T,
  pub len: usize
}
```

Listing 2.5: Slice representation

Boxed values

Listing 2.6 shows an example of how a linked list can be represented with an enum. Each list item is either a value and a pointer to the next item, as in `Cons`, or a termination value, as in `Nil`. The `Cons` is a name given by us, just like the name `List`. One important thing to notice in this example is the usage of a `Box<...>` instead of the mentioned pointer. As discussed earlier, `Rust` provides abstractions on top of its raw pointers, and the `Box` is an example of this in action. A boxed value is simply a value that is stored on the heap, with its owning handle stored in a `Box` structure. The `Box` pointers are managed by `Rust`'s ownership mechanisms (described in Section 2.1.5). They are, unlike raw pointers, guaranteed to be *safe* to use. This structure implements the same operators that are otherwise associated with pointers, so they are semantically the same for this piece of code.

```
enum List<T> {
  Cons(T, Box<List>),
  Nil,
}
```

Listing 2.6: Definition of Linked List

Pattern Matching and Destructuring

Pattern matching is a powerful language construct of `Rust` that resembles the `switch` statement from `C`. It is possible to match against any value or variable in the language, and branch to different blocks of code based on the outcome of the `match`. Another important feature of the `match` statement is that it needs to be *exhaustive*, which means that all possible outcomes of a `match` need to be considered, otherwise `Rust` will issue an error during compilation. This is contrary to `C`, where only primitive values can be used in a `switch` statement, and there is no requirement to cover all switch cases, i.e. the `default` keyword is not required.

An example of pattern matching on the `Option` type is given in Listing 2.7. We can see from the example that the match can be used to *destructure* the matching value in order to get hold of its enclosing value. We can also see that both `Some` and `None`, i.e. all possible outcomes of the `Option`, are being considered in the example.

```rust
// Bind the value 'Some(42)' to the variable 'num'
let num: Option<u32> = Some(42);

match num {
  // Bind the Option's enclosing value to the variable
  // 'number' and print its value
  Some(number) => println!("{}", number),
  // Otherwise do nothing
  None => (),
}
```

Listing 2.7: Matching an `Option`

Traits

Traits in `Rust` are similar to Interfaces in Java - they are used to facilitate code reuse and polymorphism. A `trait` can define a set of methods that other objects can implement, and in contrast to Java's Interfaces, a trait also supports default implementations for its methods that an object can inherit directly. The definition of one of `Rust`'s more integral traits is the `Iterator` trait, which is shown in Listing 2.8. An iterator can be used to manipulate stream- or list-like data structures, where the trait implements functions like e.g. `map`, `zip`, and `filter`, which are modifier functions that are commonly found in functional programming languages.

```rust
pub trait Iterator {
  type Item;
  fn next(&mut self) -> Option<Self::Item>;
  fn size_hint(&self) -> (usize, Option<usize) { ... }
  // ...
}
```

Listing 2.8: Definition of the Iterator trait

Loops

`Rust` provides the two loop constructs known from `C`, `for` and `while`, in addition to `loop` for infinite loops. The `for` loop is not the conventional `for (initialize; condition; increment)` that is common in other languages. In `Rust` the `for` loop operates on iterators. `Rust`'s `for` statement is merely syntactic sugar for a `loop` with an internal `match` around the iterator's `next()` function. Listing 2.9 shows how a `for` loop is used to loop over a vector of numbers. This code is de-sugared by `Rust` into the equivalent (simplified) code shown in Listing 2.10.

```rust
let values = vec![1, 2, 3];

for x in values {
  println!("{}", x);
}
```

Listing 2.9: An iterator `for` loop

```rust
let mut it = values.into_iter();
loop {
  match it.next() {
    Some(x) => println!("{}", x),
    None => break,
  }
}
```

Listing 2.10: `Rust`'s `for` loop de-sugared to a `loop`

Closures

A closure is an anonymous function that closes around the environment that it is defined within. Any freestanding variables that are defined in this environment are accessible to the closure. A closure can be used as an argument to another function, or be returned from a maker function.

```rust
fn main() {
  let (nums, limit) = (vec![1, 2, 3, 4], 3);
  let filtered: Vec<&u32> = nums.iter()
                                .filter(|&el| *el < limit)
                                .collect();
  println!("{:?}", filtered); // prints: '[1, 2]'
}
```

Listing 2.11: Using a closure to filter the entries of a vector

Listing 2.11 shows how a closure can be used to filter a list of numbers. It also demonstrates one of the `Iterator` trait's many use cases. The example initializes a vector with four numbers and makes an iterator by calling the `iter()` function. Once the iterator is acquired, the `filter()` function is called with a closure as an argument. The expression `|&el| *el < limit` defines the closure, which takes an argument `el` and returns a `bool`. The `limit` is a free variable that is found in the scope of the `main` function; this variable is part of the environment that is *enclosed* by the closure. When the `collect()` function is called, the closure is executed with every element in the vector, and they are collected into a new vector if the closure's condition is satisfied.

2.1.3 Organization

A `Rust` library or executable is organized into a *crate*, and such a crate can consist of many *modules*. These modules are used to split up the library into separated pieces of code, which gives it a logical structure. The crate is a shareable part of `Rust` code that can be included into other projects and libraries. The modules are the hierarchical means of organizing a crate, and it ensures that the design is modular. This gives the programmer the ability to import only the components of the library that is needed for a particular program. Figure 2.1 shows a few of the modules contained within the `Rust collections` crate.

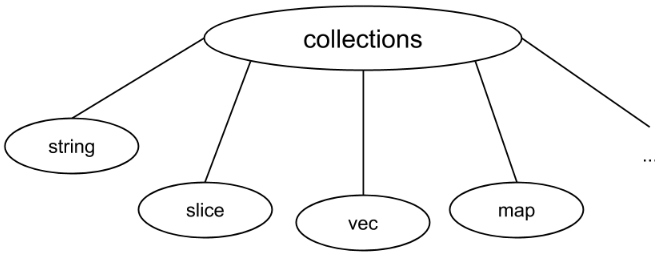


Figure 2.1: Some of the modules in the `collections` crate

The `Rust` compiler comes bundled with a handful of standard libraries that are used as a basis for almost all third party libraries and executables. By default, every `Rust` application is linked with the `Rust std` library, which *re-exports* functionality from the standard libraries, like e.g. the `collections` crate.

2.1.4 Zero-cost Abstractions

Definition of Memory Safety

To achieve full memory safety, we have to remove all forms for memory leaks and dangling pointers to invalid memory. This implies one *memory deallocation* for every respective *memory allocation*.

One of `Rust`'s goals is to achieve performance similar to `C` and `C++` while providing complete memory safety. `Rust` aims to achieve this with *zero-cost abstractions*, which means that the various high-level language constructs it implements does not come with an execution overhead. This section gives a detailed example of one of `Rust`'s zero-cost abstractions.

Abstractions, in the form of references and pointers to objects or structures, and how they are structured on the heap, is a common source of overhead in programming languages. Figure 2.2 shows how `Java` lays out a vector of strings in memory.

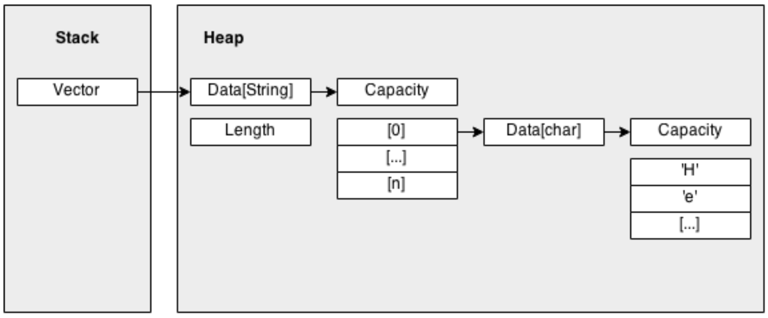


Figure 2.2: Abstractions of a Vector of Strings in Java

Fundamentally, a reference to the heap-allocated vector is placed on the stack, and the vector itself stores internal references to different strings that are placed elsewhere on the heap. If we want to access the first character of a string stored in the vector, we would have to go through four levels of indirection - two objects need to be both dereferenced and indexed. If the nesting of objects is deep, it can result in many heap-lookups in order to get the desired data.

An important part of zero-cost abstractions is the ability to define new abstractions, like a vector, that optimizes away to the bare minimum. `Rust` introduces the same zero-cost abstractions that are present in `C++`, among other programming languages. This is both important for performance, and for general purposes in order to have a deterministic and a common understanding of how the structures are laid out in the memory. Figure 2.3 shows how `C++` places a vector of strings in memory. The main difference is that the vector itself is placed on the stack, and the string data is placed directly inside the memory block owned by the vector. The important part of this example is that we are exposing the same level of abstraction to the programmer, but there are only two layers of indirection between the vector and the character data.

There is still one vital difference between the two vector abstractions. We can safely have multiple references into our vector in `Java` without worrying about what would happen if its reallocated. This happens when a vectors content grows over its capacity. However, we can end up with dangling pointers if we happen to have multiple references to our vector in `C++`, and it grows and reallocates while we are holding such a reference. This is the case because, when the vector grows and gets reallocated, references into the vector will not be updated to the newly allocated storage. These references will instead be dangling pointers into the now old and deallocated storage.

In `Rust`'s case, all structures are allocated directly on the stack, if not explicitly told otherwise, which generally allows for faster access of data. References to such stack-allocated variables can be passed around and accessed, just like in `C++`, but `Rust` also introduces a set of rules that have to be followed to safely use these references. These rules are based upon variable ownership and lifetimes, which are

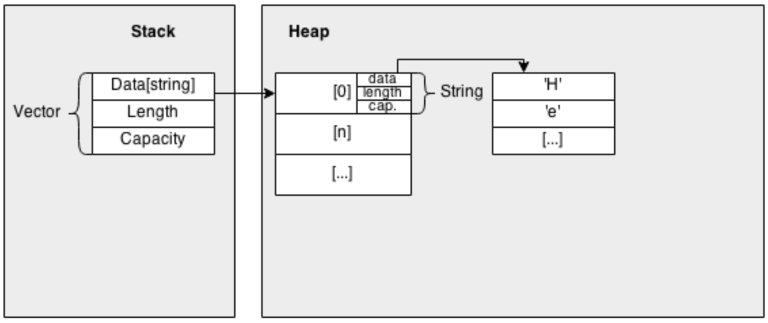


Figure 2.3: Abstractions of a Vector of Strings in Rust and C++

discussed in Section 2.1.5. A Rust program will not successfully compile if the programmer fails to properly maintain these rules.

2.1.5 Guaranteed memory safety

One of Rust's key features is its ability to maintain full memory safety without sacrificing performance. The memory safety boils down to how Rust manages variables and memory throughout the course of a program. Rust introduces a few concepts that are all centered around the *ownership* of these variables, how references to these variables can be *borrowed*, and their *lifetimes*. These concepts are defined in Rust, but much of the inspiration behind those rules come from other type-safe languages, like Haskell and OCaml, and, in particular, Cyclone's [14, 26] region-based memory management. They are defined here:

Ownership
: A value can only have one owning handle at any given moment. This ownership can be transferred to another owner. The owner is responsible for deallocating the bound value.

Lifetime
: A lifetime is a static approximation of the span of execution during which the pointer is valid. It always corresponds to some expression or block within the program.

Borrowing
: A value can be borrowed for a limited duration. In this case the owner still retains ownership and cannot deallocate the value while it is borrowed.

The ownership system is one of the zero-cost abstractions in Rust. It can be considered zero-cost because all borrow-checking and ownership- and lifetime-analysis are done statically during compilation. This makes Rust interesting to consider in a bare-metal system, as it can provide memory management without the runtime cost of a garbage collector.

Automatic Memory Management

Modern programming languages, like `Java` and `Python`, typically achieves memory safety with a *garbage collector* that runs while the program is being executed with the sole purpose of deallocating unused memory. A common implementation is a reference counted garbage collector [28] that keeps a count of the number of references to the variables and deallocates them when there are no valid references to them. The downside of such an approach to memory safety is the continuous use of resources it requires to keep track of all the references. The variables' reference counts must be altered every time they enter and leave a program scope.

Another common implementation is a stop-the-world garbage collector [28]. It works differently by regularly halting the executing program before it recursively traces all references that are accessible from the *root set* of variables. The root set consists of global variables, local variables in the stack and any variable that may be available from the current state of the registers. The memory that is accessible from these references are then marked as valid, and all the invalid memory will then become freed and accessible through new calls to the memory allocation function. The downside of such an approach is the requirement of halting the entire program in order to release the invalid memory. There are also many other techniques of garbage collection, which are often a variation of the ones already described. However, they are all problematic in resource constraint environments such as on a small embedded device, or in real-time systems where the unpredictability of program execution introduced by a garbage collector is unacceptable.

Manual Memory Management

Another approach to keeping track of the memory resources has been to give the programmer full control of every memory allocation and deallocation. This is the most common approach for systems programming languages like `C` and `C++`, where performance and predictability are important. However, it is easier to make the error of referencing invalid memory, or forgetting to free up memory that might lead the program to use all available resources over time. Memory leaks like this will eventually lead a running program to crash due to the unavailability of extra resources.

Memory Management with Ownership

`Rust` operates differently from `C` when it comes to freeing memory. Any variables holding a reference to stack- or heap-allocated memory will automatically be freed when it leaves the scope it lives in. This is done statically without any interference by the programmer. When the compiler sees that the variable (also called the *owning handle*) for the allocated memory leaves its scope, it knows that it is also lost to the program, so it will insert a call to free the memory right after it becomes unreachable. This eliminates the need for the programmer to manually do the

```rust
fn read_book(b: Book) {
  println!("You just read {} pages", b.pages);
}

fn main() {
  // ‘b’ is the owning handle to a Book
  let b = Book { name: "Gecko’s".to_string(), pages: 150 };
  // when this line is reached, ‘read_book’ takes ownership of ‘b’
  read_book(b);
  // when ‘read_book’ returns, the book is also deallocated
  // this makes it impossible to  read the book two times
  read_book(b); // <- compiler error: use of moved value: ‘b’
}
```

Listing 2.12: Example of an owned handle

memory bookkeeping. These two aspects of memory allocation and deallocation are combined into the concept of *ownership* that `Rust` incorporates. When a handle that *owns* a reference to a data segment on the heap leaves its scope, `Rust` knows that it can safely free the memory that is referenced by it because it is the *owning handle* to that memory.

An example of this ownership is shown in Listing 2.12. Only one owning handle can exist for any heap- or a stack-allocated variable at any time during program execution. This means that if the handle gets passed as an argument to a function, this function will take *ownership* of the variable by *moving* it to the new scope defined by the function. This move prevents any further use of the handle in its original scope and is necessary because `Rust` only allows one owned handle to any memory segment at any time. If two or more handles to the memory had existed at the same time, it would have resulted in several calls to `free`, one for every time the handle left the different scopes. The only way to continue using the handle in its original scope would have been to give the ownership back after using it.

Borrowing

Borrowing is introduced as an alternative to moving the ownership of the value. `Rust` allows the programmer to *lend* away access to handles by passing a reference to the variable around instead of the actual handle. Multiple *references* can exist to the same place in memory, as long as there is only one *owner* of the actual handle, and that the *owner* does not deallocate the memory before all borrowers are finished. A reference is denoted with an `&` in front of the handle, which will tell `Rust` that we are working with a reference to the handle, or that we are borrowing the handle, to the end of the active scope. Consider a modification of the previous example shown in Listing 2.13. Here, the `read_book` function is modified to accept a reference to a book instead of overtaking its ownership, thus allowing us to lend

```
fn read_book(b: &Book) {
  println!("You just read {} pages", b.pages);
}

fn main() {
  // 'b' is the owning handle to a Book
  let b = Book { name: "Gecko's".to_string(), pages: 150 };
  // only a reference to the book is given to 'read_book'
  read_book(&b);
  // it is possible to read the book two times, because 'b'
  // still lives in the scope defined by the 'main' function
  read_book(&b);
 }
```

Listing 2.13: Example of borrowing

out the book to be read as many times as we want. Since the book's owning handle lives in the scope defined by the main function, the memory will be deallocated when the program exits.

Lifetimes

The `Rust` compiler will assign a *lifetime* to every value in a program. This lifetime is used by the compiler to prevent problems like *use-after-free* by failing the compilation process if such errors are discovered. The lifetimes are, for many uses cases, inserted automatically by the compiler. This is done with a process called *lifetime elision*. Listing 2.14 provides a lifetime analysis for a simple program.

```
fn main() {
  let a = 42;   // 'a' is an owning handle to the value 42.
  {
    let b = &a; // 'b' is a reference to 'a', thus 'a' is borrowed.
  }             // The lifetime of the 'b' reference ends here.
}               // The owning handle 'a' goes out of scope
                // and deallocates the value 42.
```

Listing 2.14: Lifetime analysis

In Listing 2.15 we consider a function that takes a reference as a parameter. This shows how the compiler infers a lifetime for the function parameter. In the comment on line 1 we have included the explicit *lifetime specifier* (`'a`) as it would be inserted by the compiler.

```
// foo<'a>(x: &'a u32) { // lifetime specifier inferred by the compiler
fn foo(x: &u32) {
} // The lifetime of the 'x' reference ends here.
fn main() {
  let a = 42; // 'a' is an owning handle to the value 42.
  foo(&a);    // 'a' is borrowed by the 'foo' function.
}             // The owning handle 'a' goes out of scope
              // and deallocates the value 42.
```

Listing 2.15: Function with inferred lifetime specifier

The reader is encouraged to see the Rust Book [7] for a more in-depth explanation of ownership and lifetimes.

2.1.6 Concurrency Model

Solving both memory safety and concurrency might sound like two entirely different problems, but the ownership system described in Section 2.1.5 actually turned out to go a long way of being the solution of them both [1]. While we do not utilize or focus on the concurrency of Rust in this project, it is still a very important feature for the language, so it will be shortly introduced in this section.

As already mentioned, Rust's ownership system helps us to reason about the liveliness of variables, and it helps us to catch errors like use-after-free, and data races by not allowing us to have multiple references to the same mutable data. This makes it possible to describe and utilize many powerful idioms and paradigms, and concurrency models that are based on these core features of the language. Thus, Rust's way of providing concurrency is made possible because the ownership system guarantees that it will be safe. Indeed, the core concurrency functionality in Rust is merely an abstraction that is defined in the standard library, is is not a feature in the language itself. This is an important distinction, because it allows for any number of third party concurrency libraries to evolve based on the same core principle of ownership, without being dependent on the concurrency idioms that are provided as part of the standard library.

2.1.7 Unsafe Code

Rust's strong type system and static guarantees about memory safety goes a long way in verifying the safety of programs, but for certain programs, the restrictions set by the compiler might be too conservative. Many programs that exist are indeed safe, but still not possible for the compiler to verify. Examples of code that the compiler cannot verify is code that dereference *raw pointers*, or code that utilize Rust's FFI or directly call on any of the compiler intrinsics functions. Raw pointers in `Rust` are similar to normal pointers in `C`, which means that they are not constrained by `Rust`'s ownership rules, and thus allows for aliasing to mutable data - they are not even guaranteed to have non-null values. The compiler can not protect against use-after-free errors or dangling pointers when raw pointers are involved.

The ability to define new abstractions with efficient implementations is an important goal of `Rust`. Sometimes, this means that the underlying code needs direct memory access and the ability to dereference raw pointers or call into external libraries. For these tasks, `Rust` provides the keyword `unsafe`. It is important to note that this `unsafe` keyword is introduced to *keep* `Rust`'s semantics about memory safety. The programmer is responsible for maintaining the safe invariants of the compiler when using an `unsafe` block.

Unsafe Operation	**Why it is considered unsafe**
Access and update static mutable variables	Writing and reading to and from global state can lead to race conditions because every thread and scope in the program has direct access to these global variables at the same time.
Dereference raw pointers	There are no variable bindings between a raw pointer and the data it points to; thus the normal ownership rules provided by the borrow-checker does not apply to them. This means that `Rust` cannot resolve issues with race conditions or dangling pointers.
Call unsafe functions, e.g. FFI or compiler intrinsics	`Rust` can make no guarantees about the safety of `unsafe` functions. If a FFI function is called, we are leaving `Rust`'s scope and entering another language domain, and it is not possible for `Rust` to verify the safety of such code.

Table 2.2: Unsafe operations exposed through an `unsafe` block

Table 2.2 summarizes the three things that are possible to do in an `unsafe` block, and some examples of why the operations are considered unsafe. Compiler Intrinsics are functions that are provided by the compiler itself, not `Rust` and are functions that are closely related with raw pointers. These are all considered unsafe, as they provide core functionality to e.g. access and modify volatile data, transform the data of one type into another, or perform atomic operations.

It is important to note that `Rust`'s borrow-checker is still active *across* the unsafe code and that normal ownership rules still apply even though the code is unsafe. The borrow-checker can never be disabled, but for certain operations it will simply not work. Listing 2.16 demonstrates this with the same example that was used in Section 2.1.5. We can see from this example that it is not allowed to return a reference to something that is allocated *within* an unsafe block, as this can result in use-after-free issues. This also tells us that using an unsafe block is not the same as disabling all the checks in the compiler, it is merely a mechanism for the programmer to take responsibility for safety in the parts of the program where the compiler is unable to.

```rust
fn main() {
  let name = unsafe {
    let b = Book { name: "Gecko's".to_string(), pages: 150 };
    // If the last statement in a block does not contain a ';'
    // then the block is turned into an expression that
    // evaluates to the value of this statement
    &b.name // <- compiler error: 'b.name' does not live long enough
  };
}
```

Listing 2.16: Attempting to return an invalid reference from an `unsafe` block

2.2 The Cargo Package Manager

`Cargo` is `Rust`'s package manager, it is an application that automates the process of building and distributing `Rust` programs. It comes bundled with the default installation of `Rust`. `Cargo` comes with a collection of tools that make building, testing, and running `Rust` programs much easier than invoking `rustc` directly. `Cargo` also defines a standard `Rust` project layout, in addition to downloading and maintaining package dependencies. This section will cover the most important features of `Cargo` and how it works, enough of what is required in order to understand the work that is described later in this project report.

2.2.1 Project Structure

Every crate, or package, built by `Cargo` requires a `Cargo.toml` file to be present in the root directory. This file is interpreted by `Cargo` and is used to determine the name of the library and executables to be built in the package. Any dependencies that the package might depend on are also specified in this file, and `Cargo` will automatically download, compile, and link these dependencies with the project. It also includes information that tells `Cargo` how the package can be compiled for different target architectures, and it is used to define different *features* of a package - a way to conditionally compile certain parts of the code present in the library.

```
hello_world
├── Cargo.lock
├── Cargo.toml
└── src
    └── main.rs
```

Listing 2.17: Minimal `Cargo` project structure

Listing 2.17 shows a standard `Cargo` project structure for an executable target. If a project contains a `main.rs` file, it will be compiled into an executable with the same name as the project (`hello_world` for this example). `Cargo` requires that this file also contains the `main` function for the program. Finally, `Cargo` also generates a `Cargo.lock` file that contains *specific* information about all packages that are used in the project. This information includes the name and version of the package and its dependencies, including any transitive dependencies they might have. This file helps `Cargo` determine if packages need to be re-downloaded, updated, or re-compiled in order for the project to be built consistently - independent on the target architecture it is built on and for.

```
cargo
├── Cargo.lock
├── Cargo.toml
├── src
│   ├── bin
│   │   ├── build.rs
│   │   ├── test.rs
│   │   └── ...
│   ├── lib.rs
│   ├── compile.rs
│   └── ...
└── tests
    ├── test_cargo_build.rs
    ├── test_cargo_test.rs
    └── ...
```

Listing 2.18: Expanded `Cargo` project structure

Listing 2.18 shows an example of a library project structure, and it is in fact a simplified version of `Cargo`'s actual structure. If the intended use of a project is to be utilized as a library for other applications, they include a `lib.rs`. This file, including its submodules like `src/compile.rs`, as presented in this example, will be compiled into a `Rust` crate. In this case, the the crate name will be `cargo.rlib`. Any files found under the `src/bin` directory will also be compiled into its own executables, and `Cargo` will automatically link the library and all of the its dependencies with these executables. In Cargo's case, every command shown in Table 2.3 has its own dedicated executable target in this directory.

A package can also contain a tests directory with integration tests, as shown above, and an examples directory with different executables that demonstrate how to use the library (this has not been included in the above example). A package can also have it's own build-routine by specifying a build script in the Cargo.toml. This file is executed prior to building the package itself, and provides the possibility to e.g. compile and link third party C libraries, or generate code prior to compilation.

2.2.2 Building and testing

As previously mentioned, Cargo comes with a collection of tools that make it easy to build and test Rust projects. The most common commands are shown in Table 2.3. Most of these tools are self explanatory, but the build and the test commands will be described a little more thoroughly in this section.

Command	**Description**
build	Compile the current project
clean	Remove the target directory
doc	Build this project's and its dependencies' documentation
new	Create a new cargo project
run	Build and execute src/main.rs
test	Run the tests
bench	Run the benchmarks
update	Update dependencies listed in Cargo.lock

Table 2.3: Common cargo commands

By invoking the cargo build command, Cargo will download and resolve all package dependencies and trigger rustc to compile and link them with each other in the correct order. When all dependencies have been built, the build script will be invoked (if it is present in the package) before the library itself is compiled. Lastly, the projects executables will be compiled if the project contains a main.rs or sources in the src/bin directory.

The cargo test command will also trigger rustc to compile the library in the same manner as cargo build, but it will leave out compilation of the project executables. When the library is compiled, any function that is marked with #[test] will be included and treated like a unit test - this is a feature from Rust itself. Cargo also treats all the sources found in the examples directory as tests together with all the integration tests. When Cargo finishes compiling the library and its executables, it will run all the unit tests, including the integration tests, but it will not run the examples.

Flag	Description
`--target TRIPLE`	Build for the target triple
`--features FEATURES`	Space-separated list of features to also build

Table 2.4: `Cargo` flags to alter the package library and executables

Both of these commands support several optional build-specific flags that are passed further on to the invocation of `rustc`. We will take extra notice to the two flags shown in Table 2.4. The `--target` flag is used if the project will be compiled for a different target architecture than the machine it is invoked on - this is necessary for our project in order to cross-compile libraries from x86 to ARM. The list following the `--features` flag will be used by `Cargo` and `rustc` to conditionally compile code that is present in the project. Consider the example shown in Listing 2.19 and its output shown in Table 2.5. From this example we can see that the definition of the `num` function will be different based on the feature flag that is passed to `Cargo`.

```rust
// src/main.rs
#[cfg(feature = "one")]
fn num() -> u32 { 1 }

#[cfg(feature = "two")]
fn num() -> u32 { 2 }

fn main() {
    println!("num() + num() = {}", num() + num())
}
```

Listing 2.19: Example usage of features

Command	Output
`$ cargo build --features one`	num() + num() = 2
`$ cargo build --features two`	num() + num() = 4

Table 2.5: Example output of features

2.3 Hardware Platform

This project targets the EFM32GG MCU developed by Silicon Labs. The following sections present the EFM32 family of microcontrollers and a couple of development kits that utilize the Giant Gecko MCU, soldered with a handful of different peripherals.

2.3.1 EFM32

ARM Cortex-M is a family of 32-bit RISC processor cores, which is intended to be used by applications that require low cost and energy-usage. These factors are crucial in modern systems and applications where energy efficiency is of great importance. For example, with the IoT [27], where it is predicted that tens of billions of devices will be connected to the Internet in the future, ranging from Super Computers down to small embedded devices that might be used to power up and control everything from cars to light bulbs via the Internet. The different processor cores of the Cortex-M family are summarized in Table 2.6.

Name	**Target features**
Cortex-M0	Lowest cost and lowest area
Cortex-M0+	Lowest power
Cortex-M1	Designed for implementation in FPGAs
Cortex-M3	Performance efficiency
Cortex-M4	DSP, SIMD, FP
Cortex-M7	Cache, TCM, AXI, ECC, double + single FP

Table 2.6: Cortex-M family of processor cores

The EFM32 family of microcontrollers are all based on different Cortex-M processors, and some of their features are summarized in Table 2.7. The focus of these microcontrollers is energy efficiency and low power-consumption in resource-constrained environments. The EFM32GG, usually referred to with the name `Giant Gecko`, is a versatile chip that is in the upper end in the Cortex-M series. This is the processor core that is targeted in this project, and for the sake of simplicity, this chip will be referred to as `Gecko`.

The microcontrollers implement several different methods for reducing the power consumption. The most important way to achieve low power consumption is by turning off the different parts of the chip that are inactive so that these parts no longer draw any power from the overall system. The EFM32 processors feature five different energy modes, or sleep modes, ranging from EM0 (Energy Mode 0), where the CPU is on, to EM4, where the processor only wakes up on specific interrupt signals. The different peripherals provided with the EFM32's operate in different energy modes. This system allows applications to utilize many different peripherals for data collection, while the processor itself is turned off. The peripherals then have the opportunity to wake up the processor on different interrupt-signals and transfer data to it in order to do general processing.

2.3.2 Evaluation boards

Silicon Labs provides a wide range of development-kits and -boards that are targeted for general development and testing of applications based on the EFM32 series. Two of these boards are available with the `Gecko`, and we have used both of them in this project. The simplest of the two is the `Giant Gecko` Starter Kit, which is depicted in Figure 2.4. This board contains a few LEDs and buttons, a couple of sensors to demonstrate a wide range of use-cases, and a segment Liquid-crystal Display (LCD) display. It also includes an expansion header that can be used to connect with third party devices and peripherals, and a JLink debug interface over USB.

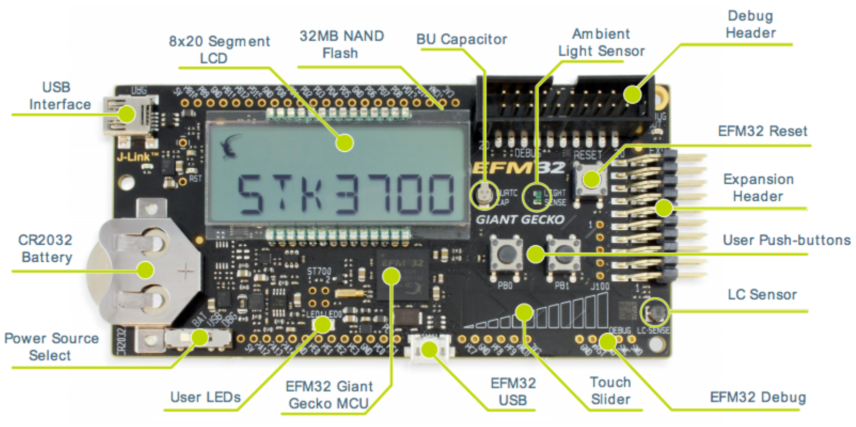


Figure 2.4: The Giant Gecko Starter Kit - EFM32GG-STK3700 [18]

As shown in Figure 2.5, the Giant Gecko Development Kit is a more complex board. It features a TFT touch Display, which is a prototyping board that exposes all the MCU pins on headers. The MCU itself is also soldered on a pluggable board, which makes the development kit a suitable system for testing a wide range of different applications. In addition to the two mentioned boards, we have also used the Biometric-EXP Evaluation board. This board was used to provide additional sensors to the `SensorTracker` application described in Section 7.4.1. The Biometric-EXP Evaluation board is shown in Figure 2.6 and connects directly with the Expansion Header available on the Starter Kit.

Name	**Processor**	**Speed (MHz)**	**Flash Memory (KB)**
Zero Gecko	ARM Cortex-M0+	24	4, 8, 16, 32
Tiny Gecko	ARM Cortex-M3	32	4, 8, 16, 32
Gecko	ARM Cortex-M3	32	16, 32, 64, 128
Leopard Gecko	ARM Cortex-M3	48	64, 128, 256
Giant Gecko	ARM Cortex-M3	48	512, 1024
Wonder Gecko	ARM Cortex-M4	48	64, 128, 256

Table 2.7: EFM32 Product Family [21]

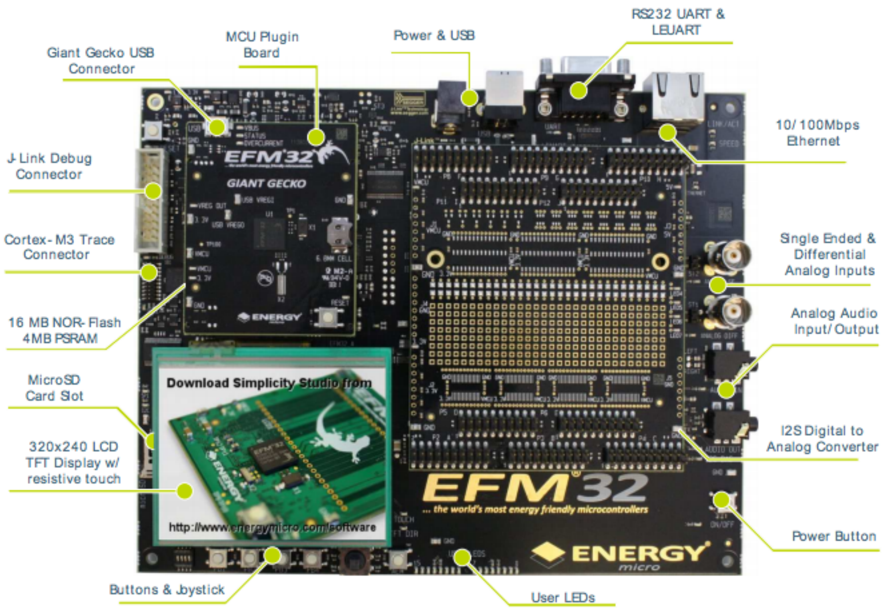

Giant Gecko USB Connector
MCU Plugin Board
Power & USB
RS232 UART & LEUART
10/100Mbps Ethernet
J-Link Debug Connector
Cortex-M3 Trace Connector
Single Ended & Differential Analog Inputs
Analog Audio Input/Output
16 MB NOR-Flash 4MB PSRAM
MicroSD Card Slot
320x240 LCD TFT Display w/ resistive touch
I2S Digital to Analog Converter
Power Button
Buttons & Joystick
User LEDs

Figure 2.5: The Giant Gecko Development Kit - EFM32GG-DK3750 [17]

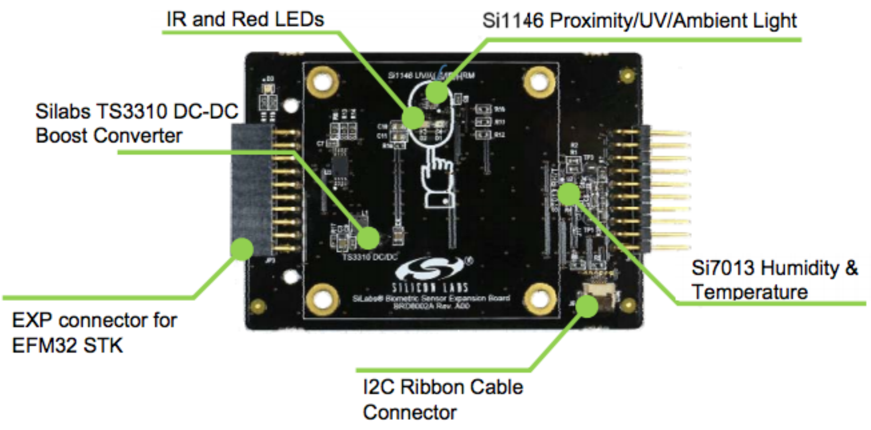

IR and Red LEDs
Si1146 Proximity/UV/Ambient Light
Silabs TS3310 DC-DC Boost Converter
Si7013 Humidity & Temperature
EXP connector for EFM32 STK
I2C Ribbon Cable Connector

Figure 2.6: The Biometric-EXP Evaluation Board - BIOMETRIC-EXP-EVB [19]

Table 2.8 summarizes the different hardware devices that are referred to throughout this report. The original device-names are shortened in order to simplify reading.

Product Name	**Description**	**Short name**
EFM32GG990	The Giant Gecko Microcontroller	`Gecko`
EFM32GG-STK3700	Giant Gecko Starter Kit	`STK`
EFM32GG-DK3750	Giant Gecko Development Kit	`DK`
BIOMETRIC-EXP-EVB	Biometric Sensor Expansion Board	`BIO-EXP`

Table 2.8: Hardware devices

2.3.3 Peripherals

Figure 2.7 shows a block diagram of the Giant Gecko. The Cortex-M3 and its memory can be found in the upper left corner. It is evident from the diagram that the MCU is connected to all other peripherals over a 32-bit bus. This section will briefly introduce the peripherals that are relevant in this project. We will describe what they can be used for and why they are important, but we will not go into detail on how they work. These details can be found in the Giant Gecko reference manual [20].

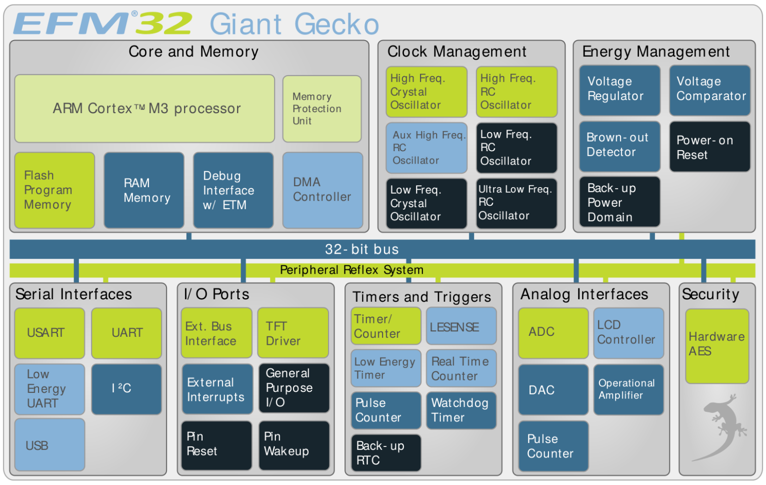


Figure 2.7: Giant Gecko block diagram [20]

Communication is important in every modern computing system, and the `Gecko` supports a handful of different serial communication protocols through different peripherals. The USART, and the Universal Asynchronous Receiver/Transmitter (UART), together with the Inter-Integrated Circuit Interface (I^2C), are serial protocols that allow for efficient communication between a high range of external devices. Different areas of use can be e.g. reading and writing to SD memory cards or transferring data over a serial interface to a computer. Peripherals like the USART and the UART can be used in combination with DMA, which is useful for energy constrained applications. This combination makes it possible to implement applications that can gather data from a range of external sensors, and transfer or store it to other peripherals with minimal interaction from the CPU.

GPIO is used for pin configuration and manipulation of the MCU pins, and it is often used to configure the pins that are required by other peripherals. Simple Push Buttons and LEDs are configured with the GPIO, and e.g. the USART needs to have configured at least two GPIO pins for both receiving and transmitting data.

Many applications are used to gather data by measuring different sensors and signals. The ADC is a peripheral that is used to measure analog signals, like e.g. sound or light intensity, and convert them to digital signals. Oppositely, the Digital to Analog Converter (DAC) can be used to convert digital signals back to e.g. analog sound signals.

Timers are another important peripheral type; the `Gecko` supports a number different timers that operate with different frequencies and at different energy levels. The Timer peripheral is used to generate signals at specified frequencies. These signals can be software interrupts to the CPU or other peripherals, which in turn, without intervention from the CPU, can be used to e.g. initiate a DMA transfer over UART at timed intervals. The RTC is another timer that works at low energy levels, which is useful for energy constraint applications.

2.4 Software Libraries

This section presents the different software libraries that we have utilized and interfaced with throughout this thesis. These are libraries written specifically for the EFM32's (or the Cortex-M's) to increase the level of productivity when programming the MCUs. Table 2.9 shows the software stack that is provided with the `Gecko`, which is presented throughout the following sections.

Library	**Description**	**Source**
CMSIS	The Cortex-M Hardware Abstraction Layer (HAL)	ARM
`emlib`	The Energy Micro Peripheral Support library	Silicon Labs
`emdrv`	The Energy Micro energyAware Drivers	Silicon Labs
`newlib`	`C` library for embedded systems	GNU ARM Toolchain

Table 2.9: EFM32 software stack

2.4.1 CMSIS

The Cortex Microcontroller Software Interface Standard (CMSIS) library is a HAL provided by ARM for their Cortex-M CPUs. It is divided into a few modules, namely, Core, DSP, RTOS and SVD. Most of these modules are not relevant for this project, only the Core module is. It provides functionality to control interrupts though Nested Vector Interrupt Controller (NVIC), manages the system clocks, and provides program tracing through Instrumentation Trace Macrocell (ITM). The different peripherals that come with ARM's CPUs are memory mapped, which means that reading and writing to certain addresses can be used to modify the peripheral's internal registers. This is explained in greater detail in Section 5.1.

2.4.2 Emlib

The `emlib` peripheral Application Program Interface (API) by Silicon Labs is a general library written in `C` that provides functionality to control the vast range of peripherals that are supported by the EFM32's. It provides a thin layer of abstraction over each of the peripherals' registers, which are memory-mapped as described in Section 5.1, and it is built on ARM's CMSIS.

The API is divided into separate files that define interfaces for modules such as ADC, DAC, Timer, and DMA, and it provides functions to easily control sleep modes and interrupt handlers. The library functions are exposed in three different API patterns, either as standalone utility methods, singleton object methods, or `C` object oriented fashion. Examples of these patterns are shown for the `gpio` module in Listing 2.20, the `RTC` in Listing 2.21, and the `timer` in Listing 2.22.

```c
void GPIO_PinModeSet(GPIO_Port_TypeDef port, unsigned int pin,
                     GPIO_Mode_TypeDef mode, unsigned int out);
void GPIO_PinOutSet(GPIO_Port_TypeDef port, unsigned int pin);
unsigned int GPIO_PinOutGet(GPIO_Port_TypeDef port,
                            unsigned int pin);
```

Listing 2.20: Standalone functions to configure the GPIO

```c
void RTC_Init(const RTC_Init_TypeDef *init);
void RTC_Enable(bool enable);
uint32_t RTC_CompareGet(unsinged int comp);
void RTC_CompareSet(unsigned int comp, uint32_t value);
```

Listing 2.21: RTC module treated as a Singleton object

```c
void TIMER_Init(TIMER_TypeDef *timer,
                const TIMER_Init_TypeDef *init);
void TIMER_Enable(TIMER_TypeDef *timer, bool enable);
void TIMER_TopGet(TIMER_TypeDef *timer);
void TIMER_TopSet(TIMER_TypeDef *timer, uint32_t val);
```

Listing 2.22: Timer module configured in C Object Oriented fashion

2.4.3 Emdrv

Another library provided by Silicon Labs is called emdrv, and it provides higher-level drivers for some of the more general EFM32 peripherals. Commonly used modules with common usage patterns usually have their own drivers that make them easier to initialize and use. Examples of modules that have their own drivers are the flash memory, which features a common read-write pattern, and the GPIO module, which exposes a common pattern for registering handler functions to be executed when an event is triggered.

2.4.4 Newlib

newlib is a C library that is implemented specifically to be used by embedded devices. Most notably, this library defines heap memory management facilities through malloc, realloc and free. These base functions are needed in order to compile both emlib and emdrv, and Rust's alloc library. The functions in newlib are used directly by the C libraries, or in Rust through RCL, which exposes the memory management symbols mentioned above. This library is distributed as a part of the GNU ARM Toolchain [3], which is a C compiler targeting the ARM architecture.

2.5 The Zinc Project

The Zinc [11] project tries to write a complete ARM stack, similar to that of CMSIS, but written completely in Rust and assembly, and with no interference of C. Zinc is an attempt at applying Rust's safety features to bare-metal systems, but it is still in early development. The project have primarily focused on supporting two different ARM development boards, the EFM32 are not part of these.

One of Zinc's main features is the ability to safely initialize a program's peripherals with a *Platform Tree* specification, which has the ability to statically catch any mis-configured MCU pins or peripherals during compilation. This setup-routine guarantees that all the peripherals gets initialized correctly. This Platform Tree is realized with a Rust *compiler plugin*, which means that Zinc can hook on to rustc's internal compilation routine, and verify the correctness of the platform specification that it is currently attempting to compile.

An example program that demonstrates the Platform Tree is shown in Listing 2.23. We have left out parts of the clock and os specifications to make the example more clear. We can see from this example that we define a platform for the LPC17 MCU, and initialize the main MCU clock, a Timer peripheral, and configure a GPIO pin as a LED. If Zinc notices that e.g. a LED and a Timer is configured to use the same MCU pin, it will exit the compilation with an error message. In the os block we specify that we want access to the Timer as timer and the LED as led1, Zinc will handle the task of initializing the peripherals and pass them as arguments to the run function.

```
platformtree!(
  lpc17xx@mcu {
    clock { source = "main-oscillator"; /* ... */ }
    timer { timer@1 { counter = 25;  divisor = 4; } }
    gpio { 1 { led1@18 { direction = "out"; } } }
  }
  os {
    args { timer = &timer; led1 = &led1; }
    /* ... */
  }
);
// Blink the LED every second
fn run(args: &pt::run_args) {
  args.led1.set_high();
  args.timer.wait(1);

  args.led1.set_low();
  args.timer.wait(1);
}
```

Listing 2.23: Simplified example usage of Zinc's Platform Tree

Although the Zinc project did not end up as part of our platform, we have used it for inspiration during design and development. In Chapter 9 we discuss the problem that arises with mutable aliases to hardware peripherals, and look at how Zinc's approach of handling peripheral initialization can help to provide a safer abstraction layer over the hardware, with respect to our platform.

2.6 Microcontroller Startup

This section describes the process of starting a program on a bare-metal system. The `main` function is typically considered as the starting point of a program. While this can be true from the programmer's point of view, in this section, it is evident that that is not usually the case. This section will present the reader with what occurs prior to the program reaching the `main` function.

2.6.1 Prelude

Before we look at the start of execution, lets look at the process between compilation and execution. The compiler outputs object-files which the linker combines into a `elf` file. This file is loaded into the microcontrollers Read Only Memory (ROM) Flash memory. Then, the reset signal is sent to the CPU to start execution.

2.6.2 Executable and Linkable File Format

`elf` is a file format for storing code and data for a program. This file format can be loaded onto a microcontroller and executed. For our purposes, this format defines three interesting sections, namely **.text**, **.data**, and **.bss**. Table 2.10 describes the content of the these sections.

ELF Header	**Header describing size of sections**
.bss	Logical section for zero-initialized data
.text	Read-only section for code and constants
.data	Section containing values for non-zero initialized data

Table 2.10: Sections of `elf` file format

The **.text** section contains the program code and any read-only data defined in the code. Strings are, for instance, stored in the **.text** section as read-only. The **.data** section contains the values for non-zero initialized data. The **.bss** section is a logical section so it is not really stored in the file. The header specifies the size of the **.bss** section, which describes the size of the zero-initialized data in the program.

2.6.3 Before main

All static data must be initialized before the `main` function starts executing. The data is divided into two categories; zero and non-zero initialized. The non-zero initialized data is contained either in the **.text** (read-only-data) or **.data** sections of the `elf` binary. On the chip, the **.data** section resides in flash memory, as these data structures might change at runtime they must be copied into RAM. The **.text** section contains the instructions and read-only data, this data does not need to be copied as they can be read directly from flash at runtime. All zero-initialized data is represented by the **.bss** section in the `elf` binary. A portion of RAM corresponding to the size of the **.bss** section must be set to zero.

Copying the **.data** section into RAM is handled by the `ResetHandler` function shown in Listing 2.24. Before the RAM is initialized, the `ResetHandler` calls a `SystemInit` routine, which can be used to set up the external RAM for the `Gecko`. The function is the real entry point of the program and is executed when the CPU receives the reset signal.

```
// Variables set in linker script
extern etext;      // address of .data segment in FLASH
extern data_start; // start of .data segment in RAM
extern data_end;   // end of .data segment in RAM
void ResetHandler() {
  SystemInit();
  for (i=0; i<data_end - data_start; i++){
    RAM[data_start + i] = FLASH[etext+i];
  }
  _start();
}
```

Listing 2.24: The MCU `ResetHandler`

After the `ResetHandler` has copied the non-zero initialized data into RAM, it calls the `_start` function in the `C` runtime. The `_start` function finds the size of the **.bss** section, which describes the size of zero-initialized area in RAM. It then calls on the `memset` function to zero out the RAM, before it goes on to call the `main` function defined by the programmer.

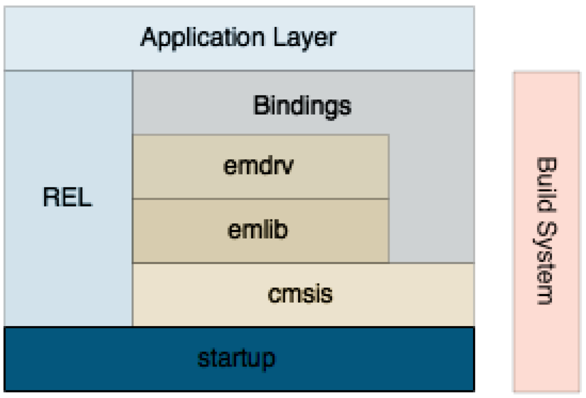
```
// Variables set in linker script
bss_start; // start of .bss segment in RAM
bss_end;   // end of .bss segment in RAM

void _start() {
  memset(bss_start, 0, bss_end - bss_start);
  main(); // User defined main function
}
```

Listing 2.25: `C` runtime start routine

Chapter 3

Startup for Rust



The `startup` module handles the process of starting a `Rust` application on the Microcontroller Unit. This module is a foundation for the `RustyGecko` platform, but it can be used in isolation to run a program on the MCU without any dependencies.

This chapter describes two important parts of a `Rust` program that needs to be configured correctly for the language to be functional with the `Gecko`. First, we describe how we configured a `Rust` program to become an executable for the `Gecko`. At the end of this chapter we describe how we get hardware interrupts to trigger interrupt handlers implemented in `Rust`.

3.1 Booting Rust on the Gecko

The contents of this section explains how the startup process described in Section 2.6 is implemented for a `Rust` program. The process for `Rust` is identical to the process in `C` because `Rust` only allows *constant initialization* before the `main` function. Therefore, we are able to reuse standard runtime components that are available in the `C` embedded toolchain.

Silicon Labs' software suite provides the `ResetHandler` and a linker script for the EFM32 microcontrollers. The linker script defines the memory layout for the `Gecko`, and this is initialized when the `elf` binary is flashed to the MCU. The `arm-none-eabi-gcc` toolchain provides an implementation of the `_start` routine that is defined in the `C` runtime. This routine is called from the `ResetHandler`, as described in Section 2.6, which in turn calls into the `main` function defined in the `Rust` executable.

3.1.1 Minimal Rust program to boot

There are a few modification which have to be applied to the default 'Hello World' program in order to get it to boot in a bare-metal environment. Let us first revisit the canonical version from Section 2.1 given in Listing 3.1. We can see that all we have to define is the `main` function.

```rust
fn main() {
  println!("Hello, World!");
}
```

Listing 3.1: Standard 'Hello World' in `Rust`

A `Rust` program will by default include Rust Standard Library automatically. As explained in Section 2.1.2, this library is not usable in a bare-metal program, and the changes to the 'Hello World' program mostly deals with removing the RSL.

The bare-metal 'Hello World' program, as given in Listing 3.2, does not print out the "Hello, World!" text because this would have required additional setup, and we are only concerned with the boot process in this example. In addition to removing the RSL, the `main` function is *exported* to be callable from the `C` runtime.

```rust
1  // Annotations
2  #![no_std]
3  #![no_main]
4  #![feature(no_std, core, lang_items)]
5
6  // Crate import
7  extern crate core;
8
9  // Define main function
10 #[no_mangle]
11 pub extern fn main() {
12   loop {}
13 }
14
15 // Define three functions which are needed by core but defined in std
16 #[lang="stack_exhausted"] extern fn stack_executed() {}
17 #[lang="eh_personality"] extern fn eh_personality() {}
18 #[lang="panic_fmt"] fn panic_fmt() -> ! { loop {} }
```

Listing 3.2: Bare-metal 'Hello World' in `Rust`

`#[no_std]` on line 2 in Listing 3.2 tells the `Rust` compiler not to include the standard library. Line 3 must be analyzed in conjunction with lines 10 and 11. Firstly, we must guarantee that the function can be called by the `_start` function. This is done by defining the `main` function to be a publicly exported symbol denoted by `pub extern`. The second change is to ensure that the function is callable by a `C` function. `extern` makes this possible by making the function use the `C` ABI. The last thing is to disable the `Rust` name mangling so that the `C` code can refer to the function by the unmangled name `main`. Now that the `main` function is altered to be callable by `C`, the function does not resemble the function the `Rust` compiler expects to find. Therefore we have to tell the compiler that the program does not contain a `main` function, hence the `#[no_main]` on line 3.

The last three lines are a complication due to error handling in `Rust`. These functions are used by the core library, but implemented in the standard library. Since we are not using RSL in this example we have to define the functions ourselves. The implementation shown here just ignores all error handling.

3.1.2 Storage qualifiers

As described in Section 2.6, the startup procedure initializes all global variables. In this section we look at how each storage qualifier, applicable to global variables in `Rust`, map to different sections of the `elf` binary.

```
const      RUST_CONST_ZERO: u32 = 0;       // not allocated
const      RUST_CONST: u32 = 0xFEED;       // not allocated
static     RUST_STATIC_ZERO: u32 = 0;      // .text
static     RUST_STATIC: u32 = 0xDEAD;      // .text
static mut RUST_STATIC_MUT_ZERO: u32 = 0; // .bss
static mut RUST_STATIC_MUT: u32 = 0xBEEF; // .data
```

Listing 3.3: `Rust` static initialization

In Listing 3.3, the three different types of declaring globals in `Rust` are shown. `Rust` divides between two types of global declarations, constants and statics.

A constant declaration, shown in lines 1 and 2 of Listing 3.3, represents a value. There is no need to allocate memory for globals declared as `const`, as the values can be directly inserted where they are used by the compiler.

The static globals are immutable by default, but can be made mutable by the `mut` keyword. The variables on line 3 and 4 are declared to be `static`. As these are immutable, they are allocated in the read-only section called **.text**.

On line 5 and 6 the declarations are marked with `static mut`. Here we see that the zero initializes variable is assigned to the **.bss** section in the `elf` file. On line 6 we have a non-zero value that has to be stored in Flash memory prior to execution and is copied to RAM in the `ResetHandler`.

3.1.3 Bootstrapping startup

The `Rust` program that was presented earlier in Listing 3.2 is quite obscure. For this reason the `startup` [1] library was developed in order to minimize the effort of making a new `Rust` program for the `Gecko`. This library makes the startup process more intuitive and hides all the details that were presented in Section 3.1.1.

A minimal 'Hello World' program using the `startup` crate is given in Listing 3.4. We still have to annotate the program with `#[no_std]`, but the `main` function is now much more similar to the one that was presented at the start of this section. This is due to the inclusion of the `startup` library.

```
#![no_std]
#![feature(no_std)]
extern crate startup;

fn main() { loop {} }
```

Listing 3.4: Bare-metal Hello World bootstrapped with the `startup` library

[1] `https://github.com/RustyGecko/startup/`

3.2 Handling Interrupts in Rust

Interrupts are an integral part of embedded programs, and having a native way of handling the interrupts provides a great benefit and flexibility for a programming language.

To handle interrupts on the `Gecko`, one have to register a function in the *interrupt vector*. This vector is defined in the **startup** file provided by Silicon Labs and is simply a list of function pointers defined in the **.isr_vector** section of the `elf` binary. This is the first section in the **text** segment of the binary which ensures that it is located at memory address `0x0` when the MCU starts executing. When an interrupt occurs, the microcontroller will inspect the interrupt vector and find the address of the handler function for the interrupt which occurred. Both the interrupt vector and the default interrupt handlers are defined in the **startup** file for the `Gecko`. The default implementations are simply infinite loops defined as weak symbols. These weak symbols allows the programmer to redefine the symbol elsewhere in the code in order to override this default implementation.

Listing 3.5 shows how the `SysTick_Handler` can be overridden in `C`. The `Gecko` can be triggered to cause interrupts that occur at a timely basis, e.g. once every second. This function will then be called when these interrupts occur.

```c
void SysTick_Handler(void) { /* Handler code */ }
```

Listing 3.5: Defining the SysTick Interrupt Handler in `C`

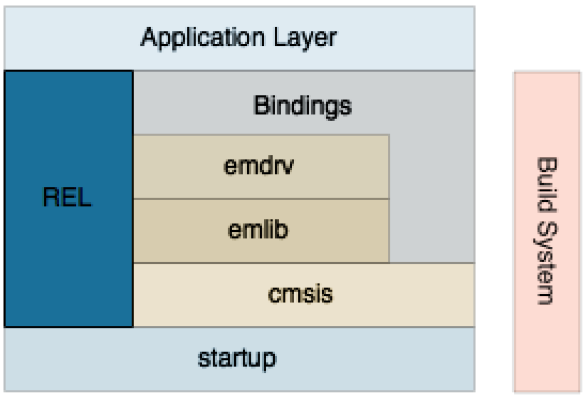
Defining an interrupt handler in `Rust` is just as easy as in `C` because of the focus on interoperability with `C` code. In `Rust`, a function can easily be defined to use the `C` Application Binary Interface required to be called as an interrupt handler. Listing 3.6 shows how to override the same `SysTick_Handler` function in `Rust`.

```rust
#[no_mangle] pub extern fn SysTick_Handlder() { /* Handler code */ }
```

Listing 3.6: SysTick Interrupt Handler in `Rust`

Chapter 4

Rust Embedded Library



The Rust Embedded Library module defines the subset of the standard `Rust` library that is applicable for bare-metal applications. This module builds on the foundation laid out by the startup module and is used by the `bindings` and `Application Layer` modules of the `RustyGecko` platform.

This chapter starts with presenting the parts of RCL that needs to be configured in order for the library to work for a new platform. We then move over to describe the standard `Rust` libraries that provide heap allocation and dynamically allocated structures. At the end of this chapter, we present our definition of the REL.

4.1 The Core Library

As described in Section 2.1.2, the RCL defines the *core* functionality of the `Rust` language. The RCL does not have any library dependencies, but in order to use the library without RSL, a few definitions are needed. These definitions are given in Table 4.1.

Functions	**Description**
`memcpy, memcmp, memset`	Basic memory management
`rust_begin_unwind`	Handles panicking

Table 4.1: External dependencies of RCL

The memory management functions given in Table 4.1 are provided by `newlib` and are exposed through the `startup` library described in Section 3.1.3.

Panicking is `Rust`'s way of unwinding the currently executing thread, ultimately resulting in the thread being terminated. A panic in `Rust` can happen, e.g. when an array is indexed out of bounds, which causes the `rust_begin_unwind` function to be called. The `rust_begin_unwind` is also defined in `startup`, but the implementation is only an infinite loop to aid debugging. In contrast, the definition of `rust_begin_unwind` given in RSL will abort the program and print an error message.

4.2 The Allocation Library

Heap allocation is introduced in a library called `alloc`. The library defines the managed pointer, `Box`, which is `Rust`'s main means of allocating memory on the heap. Also, the allocation library defines the types `Rc` and `Arc`, which are `Rust`'s *reference counted* and *atomically reference counted* heap pointers.

```rust
fn rust_allocate(usize, usize) -> *mut u8;
fn rust_deallocate(*mut u8, usize, usize);
fn rust_reallocate(*mut u8, usize, usize, usize) -> *mut u8;
```

Listing 4.1: External dependencies of the `alloc` library

The allocation library is by default dependent on `libc`, but this dependency can be broken by supplying the `--cfg feature="external_funcs"` flag to the compilation process. When breaking this dependency, the allocation library requires the functions in Listing 4.1 to be defined elsewhere. Note that these functions map directly to the `alloc`, `dealloc`, and `realloc` functions, which all are part of `newlib`. This design makes it easy to include the `alloc` library for new platforms like `RustyGecko`.

4.3 The Collection Library

The `Rust collections` library provides general purpose data structures. Out of these data structures the `Vector` (a growable heap allocated list) and the `String` (heap-allocated mutable strings) are the most notable.

As one would expect, the `collections` library depends on the `alloc` library, as it needs to allocate memory on the heap. `collections` also depends on the `unicode` library because all strings in `Rust` are UTF-8 encoded.

4.4 The Rust Embedded Library

The libraries mentioned in the previous sections provides core language constructs and dynamic heap allocation. Together they form a strong foundation for new `Rust` programs, without depending on an OS. We have composed these libraries into what we refer to as the REL, and the dependencies of these libraries are is shown Figure 4.1.

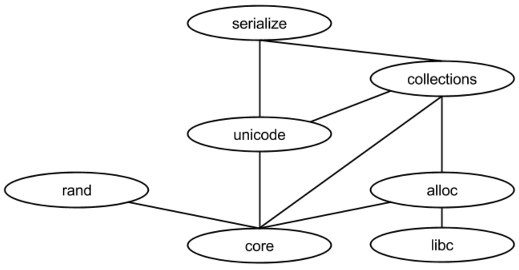
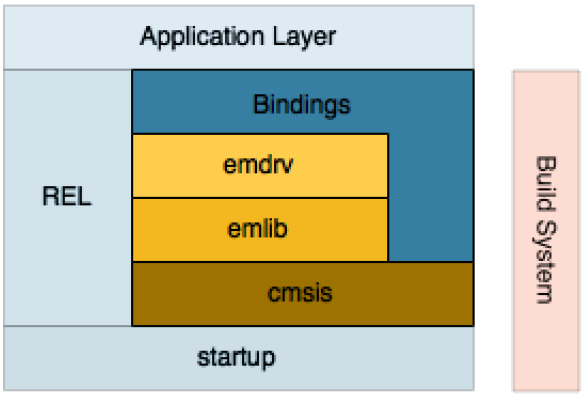


Figure 4.1: Rust Embedded Library

It is important to note that REL is just a way to provide a well-defined definition of the `Rust` language for a bare-metal system. REL is, unlike RSL, not built as a facade, it is nothing but a collection of freestanding `Rust` libraries that are suited for a bare-metal system. However, the libraries that make up REL needs to be conditionally compiled for the Cortex-M3 architecture, and this is described in Chapter 6.

Chapter 5

Binding Libraries



The `bindings` module includes the peripheral libraries provided by the MCU vendor Silicon Labs, and the architecture designer ARM. In order to make use of these libraries in `Rust`, we developed binding libraries to expose the underlying `C` implementation to the `Rust` language.

We start this chapter with a section that maps the object-oriented paradigm to hardware peripherals, which lays a foundation for how we think about the hardware throughout this thesis. In the last section of this chapter, we describe how we structured, implemented, and tested the library bindings.

5.1 Object-oriented Embedded Programming

The interface of many of the modules defined in `emlib` resembles that of objects found in object-oriented programming. In its essence, object-oriented programming focuses on organizing a computer program by looking at the data the program operates on. This is done by grouping related data into objects and defining methods that operate on the data contained within the objects.

The paradigm's essential concept can be applied to embedded `C` programming, even though the language itself does not directly define any language features to aid the design. In this section, we look at how control over the memory layout of objects, and static dispatch, can be used to enable the object-oriented paradigm in conjunction with MMIO in embedded programming. We use the memory layout of a memory-mapped ADC as an example to see how this peripheral can be represented as an object.

Static dispatch, as opposed to dynamic dispatch, is the mechanism in which the function to be called can be decided statically by the compiler, and a `call` instruction to the function can be inserted into the code directly. Dynamic dispatch, on the other hand, requires extra runtime information about the function to be called, which adds an additional layer of indirection to the function call.

5.1.1 Memory Mapped I/O

MMIO is a method for interfacing with peripheral devices in a computer system. The method entails connecting the control registers of hardware devices to the same address bus as RAM. This results in a programming model where the programmer can use common memory operations to control the devices.

Let us consider the ADC on the `Gecko`. The ADC converts an analog signal to a digital representation. The base address of the ADC on the `Gecko` is memory mapped to the location `0x40002000` in the memory space. This means that writing to a pointer that points to this address will write to the control registers in the ADC device.

Figure 5.1 shows a subsection of RAM that contains the ADC control register. Only the relevant registers for our discussion in included in the figure. It shows the control register that is used when performing a single ADC conversion. The CTRL register is used to initialize the hardware device before performing a conversion, and the CMD register is used to issue direct commands to the device like *stop* and *start*. We see that the CTRL register is at offset `0x0` from the base address of the ADC and that the CMD register is at an offset of `0x4` bytes. The two registers, SINGLECTRL and SINGLEDATA, are in order to initialize the single conversion and read the results of a conversion, respectively.

Location	**Offset**	**Name**
	...	...
`0x40002000`	0x0	CTRL
	0x4	CMD
	...	...
	0xC	SINGLECTRL
	...	...
	0x24	SINGLEDATA
	...	...

Figure 5.1: Subsection of ADC0 Memory map for the `Gecko`

5.1.2 Memory Layout of Objects

The traditional memory layout of an object in an object-oriented language is an implementation detail. This is because the fields of the object might have different sizes, and optimizations can rearrange the memory layout to optimize for size. The layout is also an implementation detail of `Rust` for the same reasons, but by annotating a struct with `#[repr(C)]`, it will ensure that it is compatible with `C`'s FFI. Objects in a language like `Java` also includes a tag field at the base of the object as a reference to the class of the object in order to provide dynamic dispatch.

```java
class ADC {
  int CTRL;
  int CMD;
  // ...
  int SINGLECTRL;
  // ...
  int SINGLEDATA;
  // ...
}
```

```c
typedef struct {
  uint32_t CTRL;
  uint32_t CMD;
  // ...
  uint32_t SINGLECTRL;
  // ...
  uint32_t SINGLEDATA;
  // ...
} ADC;
```

```rust
#[repr(C)]
struct ADC {
  CTRL: u32,
  CMD: u32,
  // ...
  SINGLECTRL: u32,
  // ...
  SINGLEDATA: u32,
  // ...
}
```

Listing 5.1: Definition of an ADC in `Java`, `Rust`, and `C`

In `C`, where classes and objects are not part of the language, structs are used to create the representations for objects. By using structs, the programmer has full control over the layout of the object in memory. The object-oriented concepts used for MMIO uses static dispatch, and the structs do not include tag fields or references to virtual tables. Listing 5.1 shows how to define a `Java` class, and `Rust` and C structs for the ADC on the Gecko. The memory layout of these objects is given in Figure 5.2.

0x0	Object tag
0x4	CTRL
0x8	CMD
...	...
0x10	SINGLECTRL
...	...
0x28	SINGLEDATA
...	...

(a) Java

0x0	CTRL
0x4	CMD
...	...
0xC	SINGLECTRL
...	...
0x24	SINGLEDATA
...	...

(b) C

0x0	CTRL
0x4	CMD
...	...
0xC	SINGLECTRL
...	...
0x24	SINGLEDATA
...	...

(c) Rust

Figure 5.2: Memory layout of objects

By comparing Figure 5.1 and Figure 5.2, we see that the memory layout of a struct defined in Rust and C has the exact same layout as the memory mapped control register of the ADC. This suggests that, if a pointer to the MMIO device is considered as a reference to an ADC object, the object-oriented pattern can be used to directly interface with the MMIO.

The layout of the Java object in Figure 5.2a could imply that the same analysis can be applied by adding an offset, equal to the size of the object tag, to the reference. This is not the case as this would map the object tag to the base address of the ADC minus 4 bytes. This location is, in the case for the Gecko, an unmapped memory section used to add padding between the ADC and the previous MMIO. Java uses this object tag to store a reference used to dynamically dispatch method calls to the object. Moreover, using the reference in place of a regular Java object would cause the method dispatch mechanism to fail.

5.1.3 Adding Object Functionality

This section shows how we add functionality called *methods* to the MMIO objects. Both C and Rust uses static dispatch. This ensures that C and Rust provide the same zero-cost abstractions when interacting with the MMIO.

Static Dispatch in C

Implementing objects with static dispatch is a straightforward process in C. Here, we define a function which takes a reference to the object as the first parameter. The function then uses the object reference in the same manner as the implicit this parameter in conventional object-oriented languages such as Java.

```c
// ADC Member function with
// explicit object reference
uint32_t ADC_DataSingleGet(
            ADC *const adc) {
  // The adc pointer is used as a
  // reference to the this object
  return adc.SINGLEDATA;
}

void main() {
  // The next section describes
  // how to instantiate MMIOs
  ADC adc;
  // Call the member function
  // passing in an explicit
  // reference to the object
  ADC_DataSingleGet(&adc);
}
```

```rust
impl Adc {
  // Rust lets the programmer
  // specify how to accept the
  // object when invoked with
  // the dot notation
  pub fn data_single_get(&self)
  -> u32 { // self is a reference
    // to the ADC MMIO
    self.SINGLEDATA
  }
}

fn main() {
  // Instantiation of MMIOs is
  // handled in the next section
  let adc = Adc;
  // The Rust compiler issues
  // a static call to the
  // member method and passes in
  // the reference to the MMIO
  adc.data_single_get();
}
```

Listing 5.2: Member methods for `C` and `Rust`, respectively

Listing 5.2 shows how to define a getter function for the ADC single conversion register, as a member method using an object-oriented pattern. We use the `impl` block to define the same behavior in `Rust`, but the methods are called with the dot notation known from object-oriented languages.

5.1.4 Instantiating a MMIO object

Now that we have shown that MMIOs can be represented as objects defined by structs, we consider how to instantiate them. Usually, an object in the object-oriented paradigm is created with a constructor and deallocated with a destructor. The constructor is responsible for allocating the object and initializing the fields with values. Analogously, the destructor is responsible for deallocating the object and any other member objects that it owns. MMIO devices have a fixed position in the memory and do not need to be allocated, and they also generally do not have any owned members. Therefore the constructor-destructor pattern is not applicable for MMIOs, but we still need to instantiate the variable that holds the reference to the MMIO and cast it to the desired type. Listing 5.3 shows how to instantiate a MMIO as an object in both C and Rust.

```c
#define ADC0_BASE 0x40002000

void main() {
  ADC* adc0 = (ADC*)ADC0_BASE;
}
```

```rust
const ADC0_BASE: *mut Adc
        = 0x40002000 as *mut Adc;

fn main() {
  let adc0 = unsafe {
    ADC0_BASE.as_mut().unwrap()
  };
}
```

Listing 5.3: Instantiating a MMIO in C and Rust

5.2 Library Bindings

This section describes the different bindings libraries that was developed as part of the RustyGecko platform. The FFI available in Rust has been used to interface with Silicon Labs' suite of C libraries used to control the Gecko. This way, we have been able to create wrappers around the API for the different peripherals that we have used in the project, without porting the core logic itself. These wrappers are called language bindings. The following sections explain the process of defining and implementing the FFI in Rust that is used to access and control the peripherals on the Gecko.

5.2.1 The Libraries

In Section 2.4 we presented the three libraries that we have created partially binding support for; CMSIS, emlib and emdrv. Here, we will take a closer look at which modules from these libraries that we have written bindings for, and our reasoning for choosing each one.

We have also written many example applications in Rust that utilize the bindings for many of the Gecko's peripherals. These examples have been a driving factor for defining new bindings. As an example, if we were to need some functionality for the ADC, we would define these bindings alongside the development of the examples. In this way, the bindings have been defined incrementally during the development of either the examples that demonstrate our libraries, or the applications described in Section 7.4.1 and Section 7.4.2.

CMSIS

Interrupt support through NVIC was the only interesting part of the CMSIS library that we have written bindings for. Most of the examples use one or several Interrupt Request (IRQ) handlers for the peripheral bindings that they demonstrate. NVIC provides utility functions for enabling and disabling the interrupt handling mechanisms of the Cortex-M3 processor.

Emlib

When we first set out to make the bindings for `emlib`, our priority was to define a viable platform for writing `Rust` applications, which we could use to evaluate the language on the bare-metal system. A list of examples that demonstrates how the bindings work is shown in Table 5.1. These are either written from scratch, or directly or partially ported from `emlib`'s examples.

Table 5.2 summarizes the modules from `emlib` that we have written bindings for, and why we wanted these bindings. A complete overview of the progress of binding `emlib` is given in Table 5.3.

Example	Purpose	Ported
`buttons_int`	Demonstrates interrupts by lighting a led on the `STK` when the respective button has been pressed.	✓
`rtc_blink`	Toggle a led with an interval of 2 seconds.	✓
`energy_modes`	Demonstrates the four stages of sleep on the `Gecko`.	✓
`uart`	Demonstrates serial communication over UART by echoing back every byte it receives.	✓
`leuart`	Similar example as `uart`, but the CPU is turned off and the functionality is moved to an interrupt handler instead.	✓
`i2c`	Sends and receives a data-buffer between two devices that supports I^2C.	✓
`joystick`	Reads analog signals generated by a Joystick that is connected to the `STK`.	
`dma`	Transfer a data-buffer from one memory location to another.	✓
`light_sense`	Uses the `STK`'s light sensor to measure the light intensity, and lights a LED when the intensity goes below a threshold	✓
`boxes`	Demonstrates dynamic memory allocation with `Box`'es, provided by the `Rust alloc` library.	
`vec`	Demonstrates dynamically allocated strings and vectors from the `collections` library.	

Table 5.1: Examples that demonstrates how the bindings work

Module	Purpose
`cmu`	The Clock Management Unit (CMU) provides functions to manage the different clocks and oscillators on the `Gecko`. This module is necessary in order to configure the clocks that are required by other peripherals to function.
`dma`	We wanted to try to use DMA for the `SensorTracker` application because it can be used to transfer data without using the CPU. This device was also used for our experiments with higher-level abstractions in Section 7.3.
`ebi`	The External Bus Interface (EBI) is used to memory map external devices connected to bus on the `Gecko`. This simplifies the process of writing data to e.g. the LCD on the `DK`.
`emu`	The Energy Management Unit (EMU) module controls the different energy modes on the `Gecko`. We needed this functionality for the `SensorTracker` application.
`gpio`	The GPIO was one of the first modules to be ported. It is used extensively throughout the bindings and in the applications.
`lesense`	The Low Energy Sensor Interface (LESENSE) can be configured to automatically collect data from multiple sensors, which we needed for the a initial version of the `SensorTracker`.
`acmp`	The Analog Comparator (ACMP) was ported alongside LESENSE, and is used to compare two analog signals and tell which one is greater.
`adc`	The ADC was needed by the `SensorTracker`, and has been used to get the internal temperature of the CPU.
`usart`	Primarily we wanted the USART for easy debugging and I/O from a computer.
`leuart`	The Low Energy Universal Asynchronous Receiver/Transmitter (LEUART) was ported a while after the USART. It has the same functionality, but it works with a lower-frequency clock and requires less energy than the USART.
`i2c`	The I^{2}C protocol has many of the same use cases as the different UART types, but it works at lower energy levels. It is used by the `SensorTracker`.
`rtc`	The RTC was an easy module to write bindings for. It is used in several examples for timing purposes, as well as in the `SensorTracker`.
`timer`	The Timer was one of the first modules to be ported. It worked as a proof-of-concept for the design of the bindings, as described later in this section.

Table 5.2: Peripheral bindings for `emlib`

Module	**#C**	**#R**	**Ported**	**Module**	**#C**	**#R**	**Ported**
`acmp`	15	3	20.00%	`lcd`	51	0	0.00%
`adc`	16	6	37.50%	`lesense`	52	21	40.38%
`aes`	19	0	0.00%	`letimer`	14	0	0.00%
`assert`	0	0	N/A	`leuart`	19	12	63.16%
`bitband`	4	0	0.00%	`mpu`	3	0	0.00%
`burtc`	28	0	0.00%	`msc`	19	0	0.00%
`chip`	1	1	100.00%	`opamp`	2	0	0.00%
`cmu`	45	7	15.56%	`part`	0	0	N/A
`common`	0	0	N/A	`pcnt`	23	0	0.00%
`dac`	16	0	0.00%	`prs`	4	1	25.00%
`dbg`	4	0	0.00%	`rmu`	6	0	0.00%
`dma`	22	8	36.36%	`rtc`	14	13	92.86%
`ebi`	42	9	21.43%	`system`	11	0	0.00%
`emu`	24	17	70.83%	`timer`	27	24	88.89%
`gpio`	33	31	93.94%	`usart`	26	6	23.08%
`i2c`	17	6	35.29%	`vcmp`	29	0	0.00%
`idac`	0	0	N/A	`version`	0	0	N/A
`int`	2	2	100.00%	`wdog`	5	0	0.00%
				total	593	167	28.16%

# C - Number of functions exposed by `emlib`
# R - Number of functions bound by bindings

Table 5.3: Bindings progress for `emlib`

Emdrv

As with `emlib`, it was not a goal to fully support all available peripheral drivers that are available in `emdrv`. The project includes two examples that demonstrate how to use the flash driver, they are explained in Table 5.4.

Example	**Purpose**	**Ported**
`flash`	Demonstrates reading and writing to the `STK`'s flash memory.	✓
`light_measure`	Based on the `light_sense` example from Table 5.1. The results from measuring the light intensity is saved to flash. When the user presses a button the `STK` will initiate a transfer that reeds all the data stored to flash and transmits it over a USART connection.	✓

Table 5.4: Examples that demonstrate how to use the flash bindings

The drivers that we have partially implemented bindings for are summarized in Table 5.5. They are not that hard to grasp or use since they are all fairly small.

Driver	Purpose
`dmactrl`	This binding only exports one function to return a standard *DMA Descriptor* which is used to initiate a DMA transfer.
`flash`	The flash driver adds an abstraction layer over a flash memory, and exposes functions to *initialize*, *read*, *write* and get the *device info*. The Driver is used by the `SensorTracker`.
`gpioint`	This driver is ported from `C` to `Rust`. The implementation differs slightly between the two versions, but the functionality is the same. The reasoning for porting this driver is described in Section 7.1.
`i2c`	This driver is used by the `SensorTracker` application. It exposes functions to initialize a commonly used I^{2}C data transfer configuration.
`tft`	This binding exposes one function to initialize the TFT screen on the `DK`. It is used in the `CircleGame`.

Table 5.5: Driver bindings for `emdrv`

5.2.2 Defining the Bindings

The `emlib` module for controlling the `Timer` peripheral [22] works as a good example to demonstrate what the `Rust` bindings look like. The module is fairly small, it mostly exposes functions to set up and initialize four different timers that can be used for up, down, up/down, and input- and output-capture. The program shown in Listing 5.4 is an example of initializing the `Timer0` peripheral on the `Gecko`. Note that this is not a complete working example, it only shows the most important parts required to use the Timer module.

```c
// Select TIMER0 parameters
TIMER_Init_TypeDef timerInit = TIMER_INIT_DEFAULT;
// Enable overflow interrupt
TIMER_IntEnable(TIMER0, TIMER_IF_OF);
// Enable TIMER0 interrupt vector in NVIC
NVIC_EnableIRQ(TIMER0_IRQn);
// Set TIMER Top value
TIMER_TopSet(TIMER0, TOP);
// Configure TIMER
TIMER_Init(TIMER0, &timerInit);
```

Listing 5.4: Initializing a Timer in `C`

First, an initialization structure for the Timer module is acquired. This structure has fields to configure many different properties of the Timer, in the same way as described in Section 5.1.1. The next lines enable interrupts for the Timer, and the NVIC interrupt vector is set up to call the function shown in Listing 5.5 every time an interrupt it triggered by the Timer. Note that this function is called implicitly by the runtime as Section 3.2 describes. All this function does is to clear the interrupt signal and toggle the value of a LED. We can imagine an application where the Timer is configured to trigger an interrupt every minute to toggle the LED, and in between the interrupts the MCU can be put to sleep in order to save power. Interrupts like this are an important part of programming the `Gecko`. They can be used for an asynchronous programming model where the application is defined by the code in the different interrupt handlers, and like in the example above, the MCU can be put to sleep in between interrupts.

```c
void TIMER0_IRQHandler(void) {
  // Clear flag for TIMER0 overflow interrupt
  TIMER_IntClear(TIMER0, TIMER_IF_OF);
  // Toggle LED ON/OFF
  GPIO_PinOutToggle(LED_PORT, LED_PIN);
}
```

Listing 5.5: Timer interrupt handler

The equivalent program written in `Rust` is shown in Listing 5.6. Semantically, they are the same, but the usage differs slightly, which is natural since we are using a higher level programming language. Instead of calling functions that are included through a `C` header file, we are calling functions that are available through a `Rust` module. For example, the `enable_irq` function is part of the `nvic` module. This modularization of peripherals can help to make the code less verbose by partially including modules. It is also worth to notice the difference between how the `Timer0` structure can be treated like an object with its own member methods in `Rust`, instead of being passed as the first parameter to every function that requires it, like in `C`.

5.2.3 Exposing Static Inline Functions to Rust

In order to work with structures and enums originally defined in `C`, we had to redefine them in `Rust` and mark them with `#[repr(C)]` so that `Rust` can guarantee that the data-elements are `C` compatible. The header files in the peripheral API also define many functions as `static inline`, which only make the functions accessible to the program that includes the header file. Since it is not possible to include `C` header files directly in `Rust`, we had to expose these functions through one extra layer of `C` code. As an example, the `TIMER_IntEnable` function is defined as `static inline` in `em_timer.h`. In order to call this function through the `C` ABI in `Rust`, we had to expose it through the file `timer.c`, as shown in Listing 5.7.

```rust
// Select TIMER0 parameters
let timer_init = Default::default();
// Enable overflow interrupt
let timer0 = timer::Timer::timer0();
timer0.int_enable(timer::TIMER_IF_OF);
// Enable TIMER0 interrupt vector in NVIC
nvic::enable_irq(nvic::IRQn::TIMER0);
// Set TIMER Top value
timer0.top_set(TOP);
// Configure TIMER
timer0.init(&timer_init);
```

Listing 5.6: Initializing a Timer in `Rust`

```c
#include "en_timer.h"

void STATIC_INLINE_TIMER_IntEnable(TIMER_TypeDef *timer,
                                   uint32_t flags) {
  TIMER_IntEnable(timer, flags);
}
```

Listing 5.7: Exposing a `static inline` function to `Rust`

In the `Rust` module definition of Timer, the function has to be made available through an `extern` block, as shown in Listing 5.8. As described in Section 2.1.7, every function available through the FFI are considered `unsafe` because `Rust` knows nothing about the function, other than its parameters and its return value. Thus, in order to make it practical to use the library in a seemingly safe manner, we wrap the calls to the foreign functions in an `unsafe` block in the respective function defined in `Rust`.

```rust
impl Timer {
  pub fn int_enable(&self, flags: u32) {
    unsafe { STATIC_INLINE_TIMER_IntEnable(self, flags) }
  }
}

extern {
  fn STATIC_INLINE_TIMER_IntEnable(timer: &Timer, flags: u32);
}
```

Listing 5.8: Defining and using a function through the `Rust` FFI

If we compare the call-stacks between calling the `timer0.int_enable` function in `Rust`, and calling the `TIMER_IntEnable` function in `C`, we can see that every function call through the FFI requires *two* extra function calls. These are simple wrappers that require extra unconditional jumps in the code, and performance-wise it is a very unnecessary overhead to have one or two extra stack frames allocated for *every* function call through the FFI. However, this overhead can be removed completely by optimizing the code during compilation so that the `C` code can be called with no overhead [5]. The extra function call due to the static inline wrapper on the `C` side of the interface will be removed by a trivial function inlining, as the only contents of the wrapper is a call to the actual function. Additionally, by enabling Link Time Optimization (LTO) during the compilations, LLVM will inline the `C` implementation into the code for the `timer0.int_enable` function in `Rust`. This results in the same performance and similar call-stacks for both `C` and `Rust`. This is a working example of one of `Rust`'s many zero-cost abstractions, enabled through the interoperability with the `C` ABI and exploiting features given by LLVM.

5.2.4 Naming Conventions

We have tried to keep `emlib`'s naming convention across the layer of bindings. This makes it easy for anyone reading either the `C`- or the `Rust`-code to translate and understand the code between the two languages. Since every constant, enum-field, or struct-name is directly accessible by name in `C`, if the corresponding header file is included, it is important that names of such fields can be separated from each other and do not cause a naming collision.

```c
typedef enum {
  timerCCModeOff     = _TIMER_CC_CTRL_MODE_OFF,
  timerCCModeCapture = _TIMER_CC_CTRL_MODE_INPUTCAPTURE,
  // ...
} TIMER_CCMode_TypeDef;
```

Listing 5.9: Part of a Timer enum defined in `C`

As an example, two fields of an enum from `em_timer.h` are shown in Listing 5.9. From each field in the enum we can extract 1) its module name `timer`, 2) its typedef name `CCMode` and 3) its field name `Off` or `Capture`. `Rust` allows us to keep the same naming convention at the same time as utilizing its modularity. Listing 5.10 shows the enum ported to `Rust`, where both the module name and the typedef name has been left out, and only the field names have remained. However, the naming convention remains the same when the fields are used, e.g. the expression "`let mode = timer::CCMode::Capture;`" in `Rust` shows the similarity with the equivalent expression in C: "`int mode = timerCCModeCapture;`".

```rust
pub enum CCMode {
  Off     = _TIMER_CC_CTRL_MODE_OFF,
  Capture = _TIMER_CC_CTRL_MODE_INPUTCAPTURE,
  // ...
}
```

Listing 5.10: The enum ported to Rust

5.2.5 Testing

Verification of correctness is an important part of all software, whether it is done manually or with an automated test framework. This section describes a small unit test framework that was developed for testing the bindings for `emlib`.

Why Unit testing

Early on in the development phase of the `emlib` bindings we saw the need for a testing framework. This was provoked by the fact that testing software on an embedded system is a time consuming and tedious task. More often than not you find yourself running the code in the debugger, inspecting the call stack and function arguments, to ensure that the bindings are calling the correct functions, with the correct arguments. The fact about arguments has a subtle point to it.

We are working in two statically typed languages that lead the compiler to statically ensure that the correct types are passed around. However, there are no checks to ensure that the memory layout of the datatypes in `C` and `Rust` match at the borders between the two languages. Currently, the `Rust` FFI requires the programmer to redefine the `C` datatypes in `Rust`, like structs and enums, in order to call into the `C` functions that takes these datatypes as arguments. The process of verifying this manually proved to be both error prone and time consuming, which suggested the need for an automated system to verify the correctness of the bindings.

Framework

To meet this problem, a lightweight testing framework was developed which enabled this verification to be automated. The goal of the framework was to initialize the data on the `Rust` side, call functions via the FFI, and verify that the correct functions were called with the exact data as supplied. In order to do this, we made a framework that could replace `emlib`'s code with statically generated test mocks, before calling these mocked functions from `Rust` and then verify that the functions where called correctly in `C`.

The implemented framework is a small test runner that utilizes CMock[1] and Unity[1], for mocking and assertions, respectively. Given a `C` header file, the CMock library generates an *mock* implementation of the interface for the module. The test code is then compiled by linking to the mock implementation instead of the library, `emlib` in our case. In the test case, the mock can be configured to verify that our bindings are using the mock as expected. All of the unit tests were compiled into a binary that was executed on the `Gecko`, which reported back via USART whether the tests failed or ran successfully. In addition, an easy to assess feedback was given by one LED lit for failure and two LED lit for success.

An example of what the testing looks like is shown in Listing 5.13. It shows a test case that is used to verify that the `ADC_Init` function is called with a default argument.

```
fn test_init_called_with_default() {
  // FFI call to the C function below
  unsafe { adc_expect_init_called_with_default(); }

  let adc0 = adc::Adc::adc0();
  // Call the emlib bindings with a default argument
  adc0.init(&Default::default());
}
```

Listing 5.11: `Rust` side of `ADC_Init` test

```
void adc_expect_init_called_with_default() {
  static ADC_Init_TypeDef init = ADC_INIT_DEFAULT;
  // Set up the expected value on the Mock
  ADC_Init_Expect(ADC0, &init);
}
```

Listing 5.12: `C` side of `ADC_Init` test

Listing 5.13: Test case for `ADC_Init` with default values

When using mocking in unit tests, the workflow for the user seems reversed compared to standard unit tests. First, you set up the expected results by calling the `ADC_Init_Expect` function on the mock, as shown in Listing 5.12. This method is called through FFI right at the top of the test case in Listing 5.11. Then, after the expected result is set up, the test case goes on to create an ADC object by using the `Rust` bindings, and calls the `init` function that causes the FFI library bindings to be executed. When the test returns, the test runner is responsible for calling a

[1]`http://www.throwtheswitch.org/`

Verify function on the mock object. This function causes the program to fail and report its status over USART if the expected result was not met.

Figure 5.3 shows a diagram of the program flow between the *Test Runner*, the *Test Case*, the *emlib bindings* as Code Under Test (CUT), and the *emlib mock*, for when the test case above is executed. We see that the two boxes marked with *Test Case* are the pieces of code the user of the framework, presented in Listing 5.13, writes. The stippled vertical line shows the separation between Rust and C code, all the three function calls which cross this line is implemented using the Rust FFI.

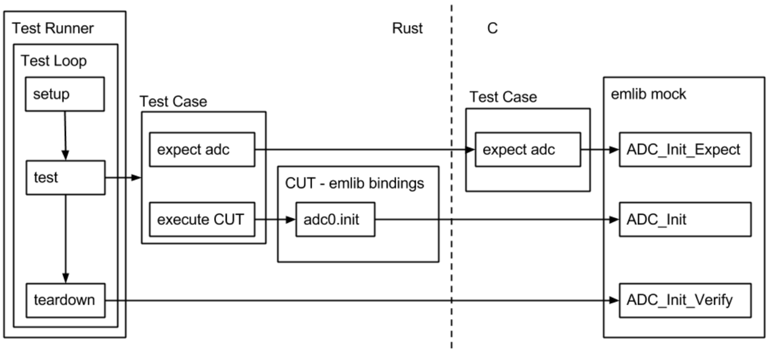


Figure 5.3: Flowchart for test framework

Rust libtest

The Rust programming language contains a testing framework within the standard library. The reasons for not using it to test the bindings is that we needed to run the tests on the Gecko. The rationale for this is that the tests are mostly checking that the datatypes used on the Rust and C side of the bindings are compatible. Therefore we need to use the proper compilers and compile the test targets for the ARM platform. Verifying that the platform-specific gcc and rustc have compatible types does not help in respect to this. Consequently, Rust's standard testing framework relies heavily on Rust's own std library, which renders the framework unusable for our bare-metal platform.

5.2.6 Discussion

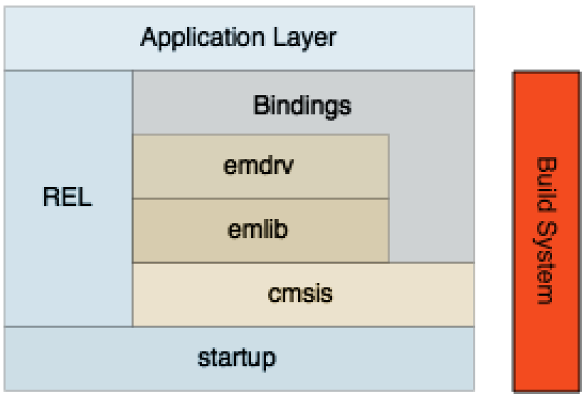
Writing the bindings for the different peripherals was a tedious work, that required careful review of the emlib source code in order to correctly port enum- and struct-definitions from C to Rust. Additionally, we had to redefine many constants, like the names of memory-mapped register bit-fields like the ones presented earlier in Figure 5.1, or values calculated from various C macros defined in header files that are used throughout the library. If they were only implicitly defined in the header files, we had to retrieve the value of the constants by debugging the source code and explicitly look up the value of these constants.

Since we have constrained our library to only support the Giant Gecko devices, we chose to manually write the bindings for the library instead of generating the bindings through some kind of automated process. There were already a couple of tools available for generating such `C`-bindings automatically, that could possibly have made the process quicker. However, we chose not to utilize such tools because of the reasons described below.

- It was quick and easy to get started with code for a new peripheral. This argument was especially important when the project started out, because we still had no clue of how the project would evolve and what it was going to look like.
- It was an advantage to depend on as few third party tools as possible, since both `Rust` and all available libraries would be unstable until the 1.0 release of the language.
- We wanted to keep the naming convention of our bindings as similar to `emlib` as possible. This would not have been easy to keep consistent with an automated process, partly because there are exceptions where these conventions do not fully hold. It is however an interesting problem that would have a higher priority if the library were ever to support more than one EFM32 device.
- We could focus on writing bindings for smaller parts of each module separately when we first needed them, which would split the work into smaller work-packages.

Chapter 6

Build System



In this chapter, we step out of the core software components of the `RustyGecko` platform to present an external, but highly important, part of the platform. The `Cargo` package manager is an integral part of the `Rust` ecosystem and facilitates sharing code and libraries with ease.

Throughout this chapter, we look at how we evolved the build system over time and ultimately migrated the process over to `Cargo`. This includes managing project dependencies and building REL and the `bindings` modules for the ARM architecture. We have also utilized a continuous integration system that has helped us to keep the project up to date with the nightly builds of `Rust`, and to ensure that the builds have been consistent across the systems it has been built on.

6.1 Manual Makefile

When the project first started out it was based upon the armboot[1] project available on GitHub. armboot is a small template project for running Rust bare-metal on a STM32 ARM MCUs. These are, similarly with the EFM32 series, also based on the Cortex-M series of ARM processor cores. We looked at armboot's Makefile to figure out what flags to pass to rustc in order to cross-compile Rust programs for the ARM architecture.

File	Description
thumbv7m-none-eabi.json	Target specification for rustc's LLVM back-end.
zero.rs	Minimal Rust runtime requirements.
blinky.rs	The executable program, it toggles the LEDs on the STK.
efm32gg.ld	EFM32 linker script.
startup_efm32gg.s	Defines the ResetHandler and the interrupt vector.
system_efm32gg.c	Used to manage the MCU Clocks.

Table 6.1: Source files included in the first build for the ARM Cortex-M

Table 6.1 lists the files included in the initial successful build[2] for the Gecko. The compilation process consisted of compiling the blinky.rs file to assembly by passing the target specification to the rustc compiler. This file was then, along with the startup_efm32gg.s and system_efm32gg.c files, compiled into object files with arm-none-eabi-gcc, and linked into an executable with the efm32gg.ld linker script, using arm-none-eabi-ld.

After we had a working Rust program for the Gecko we included the RCL, cross-compiled for ARM, and started to define peripheral bindings for emlib. The build system was later modified to generate the final executable with rustc only, instead of generating an assembly file and compile it with arm-none-eabi-gcc. We could then use arm-none-eabi-gcc to separately compile the emlib source files into an archive, and link it with the final executable. The three steps of this build routine is listed in Table 6.2.

[1]https://github.com/neykov/armboot/
[2]https://github.com/havardh/geckoboot.rs/tree/v1.0.0

Build Step	**Output**
1) Build `emlib`, system, and startup with `arm-none-eabi-gcc`.	Static `C` archive.
2) Cross-compile RCL for ARM with `rustc`.	Static `Rust` crate.
3) Build the `Rust` bindings and the executable, link it with the static libraries, generated from **1)** and **2)**, with the linker script.	Executable `elf` file for the Cortex-M3.

Table 6.2: Early build routine

6.2 Transitioning to Cargo

It was always a goal to use `Cargo` for building, distributing, and managing the packages and dependencies that would become part of this project. An obvious reason for this was to lower the bar for other potential users of the library, and to make our project as standalone as possible, so that it is easier to include and extend it as a part of other potential projects. By letting `Cargo` handle as much as possible in its build routine, it would automate a lot of the work that every programmer using the library would otherwise have to do manually.

When the project first started out it was built by compiling `Rust`'s core library and the `emlib` `C` sources separately, and then linking them with the FFI bindings by hand, as described in the previous section. While this approach worked, it was far from optimal for a number of reasons:

- `Rust` was in active development and many of its unstable APIs were going through rapid changes. Ensuring that versions of `rustc` and the `Rust` source code stayed up to date across different systems was not easy.
- Compiling and ensuring that all dependencies were consistent across builds and systems for the bindings were a tedious task. A lot of the troubles concerning this came back to the point above.
- Linking dependencies with the library required each system to have set up several different $PATHS to point to the right directories. What worked for one developer on one system might not work for a different developer on another system.
- The `Cargo` package manager was developed for exactly these purposes among others.

As already described, `Cargo` is a tool that provides many operations to build `Rust` projects that have a certain project structure. It is designed to integrate with other existing tools, like GNU Make, which has been important in building this project. When the transition to `Cargo` started, we focused on structuring the main library and its modules into the directory structure described in Section 2.2.1. By invoking the `cargo build --verbose` command, it was possible to see the output from what `Cargo` attempted to build when it failed, and then structure the project accordingly.

A big priority was to to shrink the size of the makefiles that were in the project by making them a part of the standard build process for the `RustyGecko` platform instead. Doing this would help us get a long way of ensuring that the builds done by `Cargo` could be consistent across systems. By defining a `Rust` build script and utilizing a `Rust` build-dependency called `gcc`[3], we were able to compile the `C` sources from Silicon Labs' `emlib` and link them with our bindings directly as part of the build process. Note that the `gcc` build-dependency is used as a shell to merely *invoke* the underlying `C`-compiler. In our case it is used to cross-compile with the `arm-none-eabi-gcc` compiler. By removing the dependency of manually compiling the `C` sources, it was easier to start to automatically fetch the other dependencies, like the `core` and `collections` libraries.

Because this project is for a different processor architecture than the system that it is built on, we had to conditionally cross-compile all the standard `Rust` libraries that we wanted to utilize for the ARM Cortex-M3. We could not utilize the pre-compiled libraries that are already included with `rustc`, since these only works for the current system architecture. This problem was solved by implementing a new `Cargo` build-dependency, called `rust-src`[4], whose purpose is to download the entire `Rust` source code that is compliant with the instance of `rustc` that is *currently* compiling the library. By making it a task for each build to fetch its own source code, we were guaranteed that the dependencies we used for the project would always compile, independent of the current instance of `rustc` that was installed on the system. The crates that we have fetched from `Rust`'s standard library that make up what we call REL are already described in Section 4.4, but they are also shown in Table 6.3 for the sake of completeness.

Rust library	**Purpose**
`core`	`Rust`'s core library that declares basic types.
`libc`	Types to use with `Rust`'s FFI.
`alloc`	Allows for heap-allocated variables.
`collections`	Provides common collections like dynamically allocated Strings and Vectors.
`unicode`	Required by collections for e.g. Strings.
`rand`	Generate random values.

Table 6.3: `Rust` libraries conditionally compiled for the Cortex-M3 architecture

By design, `Cargo` only supported passing two flags further on to `rustc`; `-L` and `-l`. The purpose of these flags is to tell `rustc` to link with an external library, by looking in a directory (specified with the `-L` flag), for a library with the specified name (specified with the `-l` flag). The last step in the build process involved linking the bindings and the other libraries with an actual executable for the Cortex-M3.

[3]`https://crates.io/crates/gcc`

[4]`https://github.com/sondrele/rust-src`

This was not possible to do with `Cargo` since it required us to pass a couple of extra linker-flags further on to `rustc`. The flags were needed by `rustc` in order to tell it to link with an external library for a different architecture and to include a separate linker-script that took care of booting up the executable on this architecture.

Another issue that was introduced by automatic compilation with `Cargo`, was how it structured the packages it compiled. When `Cargo` builds a project and its dependencies, it structures all the generated metadata and the compiled libraries within a `target` directory, and an extra filename gets appended to all of these libraries. This extra filename is part of a hash that is generated based on the code in the library. It ensures that each and every build is consistent and it resolves any problems that might arise if several dependencies within a project depend on different versions of the same library. This works when `Cargo` handles the entire build process. In it our case, where we had to manually compile the final executable, it turned out to be a problem because the name of the library would change every time some of its content changed. We worked around this problem by modifying the build script to store the hash generated by `Cargo` for `emlib` to a separate file, every time the library was built, and then included it in the makefile for the project.

6.3 Conditional linking with Cargo

The build process described in the previous section made it simpler to use third party libraries, but it did not solve all of our issues. The main problem that persisted was to have a good way of making the bindings themselves portable. With the setup that we had, it was easy to create new executables *within* the project, but it was hard to create new executables that *depended* on the bindings. Basically, because we had to work around `Cargo` in the final part of the build process, it also meant that *every* project that wanted to depend on `emlib` also had implement the same workarounds. Thus, we needed to solve the problem of knowing where `Cargo` would store the project metadata, and a way to get `Cargo` to compile the final executables with the extra linker-arguments needed by `rustc` in order to compile the binary for the Cortex-M3.

`Cargo` does not have much documentation over how its internal works, or how to interfere with the build process, but the documentation does mention that `Cargo` can be extended with additional *plugins*. If `Cargo` is to be invoked with a command that it does not have by default, it will query the system for this command. This means that if `Cargo` is invoked with e.g. the command `cargo foo <args>...`, it will query the system for an executable with the name `cargo-foo` and it will invoke this command with the trailing arguments if it exists. By looking at `Cargo`'s source code, we could see that every triggered build included a structure called `CompileOptions`. The arguments passed to `Cargo`'s different build commands are then used to compose this structure and trigger an internal compilation process. This process handles the compilation of all dependencies and generates all the different binaries for the current package to be compiled.

Flags	**Purpose**
`[<args>]`	The trailing argument to the command was the linker-arguments that were to be passed further on to the invocation of `rustc`. If any *args* are present, `Cargo` will append `-C link-args="<args>"` when any executables from the package is being built.
`--examples NAME`	The library had many executables located in the projects `examples` directory. This flag made it easier to compile one of these examples by specifying its name.
`--build-examples`	This flag filtered out every executable marked as an example and compiled all of them.
`--print-link-args`	This flag was included for debugging purposes.

Table 6.4: Flags for the `cargo-linkargs` subcommand

In order to solve the problems we had with building the project, we created a new subcommand called `cargo-linkargs`[5] that depends on `Cargo` itself. This subcommand was created specifically with `RustyGecko` in mind, and supports all the flags that the `cargo-build` command supports, including the flags shown in Table 6.4. We got rid of the two problems we had with building the `RustyGecko` platform once `cargo-linkargs` was working. The problem with resolving the location of generated metadata was solved implicitly just by utilizing `Cargo`, and the extra linker-arguments could easily be passed on to the invocation of `cargo-linkargs` via the project's makefile.

6.4 Continuous Integration

When we first started this project, `Rust` had reached a 1.0-alpha version. This meant that the programming language had reached a relatively stable state, but there was still big parts of the language and its standard libraries that were marked as unstable and up for review before the planned 1.0 release. The standard libraries, and third-party `Rust` libraries that have evolved in the `Rust` community, have made small guarantees about their stability, and the APIs have been subject to change without much notice.

Continuous Integration refers to the practice of testing the whole system *continuously*, for every smaller change introduced to the code base, usually with an automated test framework. Continuous Integration is advantageous to normal regression testing because it can reduce the amount of code rework that is needed in later phases of development, as well as speed up overall development time [23]. Many `Rust` projects have utilized a continuous integration system called Travis

[5]`https://github.com/RustyGecko/cargo-linkargs/`

CI[6] for ensuring that the code in the project has been compatible with the nightly builds of `Rust`. By registering our projects with Travis CI, and a community-developed service called `Rust` CI[7], we had automatic, daily builds of our projects on a third-party server. Builds were triggered every time we released a change to the code on GitHub, and every time a new nightly release of `Rust` was published. And if a build failed we would get notified of the error. By making continuous integration part of the normal build routine and review process for new project code, we had an extra step of verification that the project would build on other systems then the one it was developed on.

It is important to note that continuous integration only helped us to verify that the project could be *built*, it could not help us to prove that the compiled code would actually *work* for its target architecture. To verify that the code would work for the Cortex-M3, we had to run in on one of the MCUs that we had available for this project. An experimental process of testing and mocking the `RustyGecko` bindings is described in greater detail in Section 5.2.5.

6.5 Contributing to Cargo

As already mentioned, the ability to pass arbitrary flags further on to the invocation of `rustc` was by design not supported by `Cargo`. However, many people in the `Rust` community have wanted the ability to do so. The reasoning for not allowing arbitrary flags to be passed down is described in this section.

A compilation can go awry very quickly if it is up to the package *author* what flags should be passed to `rustc`. Instead, it should be up to the *user* of the package. This will give the author the ability to set a restriction for the library, and limit the possibilities of what a user can do with it. Different systems do not necessarily support all flags and possibilities. Thus, if a package dependency says that it is to be built in a particular way, it might not work on the system it is being built for.

On the `Cargo` project's issue tracker, several related issues concerning passing arbitrary flags further on to `rustc`, was open. All these were formalized in one issue[8] for implementing a new subcommand (called `cargo-rustc`) for the package manager. This subcommand would have allowed for passing these flags on to `rustc`, but with the restriction of only compiling a *single* binary at a time. This means that only *either* the library, a binary, an example or a test (or a package dependency), may be compiled with the extra flags, and *not* the entire package.

These rules are restrictive enough to get libraries to not depend on a set of extra flags, but loose enough so that specialized projects, like our `bindings`, can depend on it for completing the build. Indeed, the functionality proposed with

[6] `https://travis-ci.com/`
[7] `http://rust-ci.org/`
[8] `https://github.com/rust-lang/cargo/issues/595`

this subcommand would be enough to cover all the cases that we solved with our implementation of `cargo-linkargs`.

After gaining insight into `Cargo`'s internals during the development of `cargo-linkargs`, it was interesting to see if we could get this same functionality into `Cargo` itself, by implementing `cargo-rustc`. Even though `cargo-linkargs` worked great for its purpose, it was not very ergonomic for `RustyGecko` to depend on a third-party plugin to work. Especially if `Cargo` could natively support this functionality. Not only would it benefit our project, it would also give many other `Rust` projects the ability to use `Cargo` for the entire compilation process. Since both `Rust` and `Cargo` are open source projects, it was easy to get in contact with the project maintainers about the issue, and eventually submit a patch with the new subcommand. After it had been reviewed by one of the project maintainers, the patch was accepted and merged into `Cargo`'s code base. The subcommand developed as part of our build system is now a part of `Rust`'s nightly builds.

6.6 Final Library Build Artifacts

The resulting files of compiling the libraries are presented in Figure 6.1.

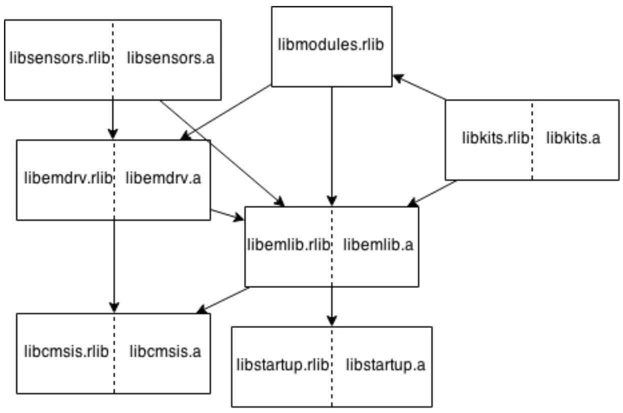


Figure 6.1: The organization files of libraries

The figure shows that all of the libraries except for `modules` consists of both a `C` static archive (`*.a`) and a `Rust` library (`*.rlib`). The `modules` library is a high level library that is built on top of the bindings for `emlib` and `emdrv`, and its implementation is described in Section 7.3. The rest of the libraries provides `Rust` bindings in the `*.rlib` part and the `C` implementations in the `*.a` portion. We also see the dependencies, denoted by the arrows, between the libraries, generally flowing from the top level abstraction down to the lower level abstractions.

6.6.1 Discussion

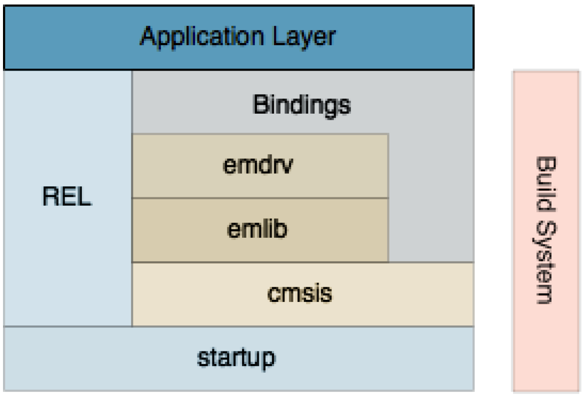
The final version of the build system for the `RustyGecko` platform is as standardized as we set out to achieve. This achievement ensures that the platform is easily reusable for anyone that is familiar with the standard `Cargo` build process. However, there are a few deficiencies in the current design. These are related to the discussion made in Section 9.1, but are discussed here in the context of the build system.

The `Rust` project is, at the time of writing, not directly targeting the bare-metal environment that we are considering in this thesis. As a result of this, we have to cross-compile each of the crates in REL separately for the ARM architecture. This process requires us to create a separate proxy project for each of the libraries that we are using. These proxies depends on the `Rust` source code to be downloaded with the `rust-src` project, as described in Section 6.2. This leads to duplicate copies of the `Rust` source code, one for *each* of the crates used in REL. Another problem with this, is the slight increase in build time introduced because the same source code is downloaded multiple times. There have, however, been discussion of providing an official crate for each of the libraries in RSL available on `Cargo`'s package repository, which would resolve this issue.

The project layout for a `RustyGecko` project is not identical to that of an ordinary `Rust` project. Both the ARM *target specification* and the *linker script* must currently be present in the top level directory for every project targeting `RustyGecko`. We would like to provide these as part of the platform in the future, to make the project layout identical to that of ordinary projects. This would further lower the bar for making use of the platform in new projects.

Chapter 7

Application Layer



The `Application Layer` is the top module of the `RustyGecko` platform. This module represents all higher-level libraries and executables built on top of the `bindings` module and the Rust Embedded Library.

Throughout this thesis, we have worked on many different project ideas that build upon the work presented in the previous chapters. A collection of the more interesting projects are presented in this chapter. First, we describe a library that was ported from `C` to `Rust`, which shows how `Rust`'s concept of *unsafe* can guide the programmer to write more secure code. In Section 7.2, we describe a library that provides a `Rust`-idiomatic way to handle interrupts, which is motivated by the desire to provide a safer way of interacting with the MCU peripherals. In Section 7.3, we apply `Rust`'s trait system to the hardware peripherals in order to build a higher-level API than `emlib`. In the last section, we describe the two applications that were developed for evaluating the `RustyGecko` platform.

7.1 Porting GPIO Interrupt Driver

This section considers a case-study of an issue in the `emdrv` library, and it was discovered while we ported the GPIO interrupt driver from `C` to `Rust`. This driver was ported to `Rust` because we wanted to issue GPIO interrupts with `Rust` function pointers, without needing to declare them with the `C` ABI (which was required by `emdrv`). The issue was discovered when annotating the `unsafe` blocks for referencing mutable global state, and gives an example of the awareness the inclusion of the `unsafe` keyword provides.

7.1.1 Presenting the Problem

The `gpioint` driver lets the user register a callback function to be called when an interrupt occurs at a given GPIO pin. It is implemented with a global mutable list of 16 function pointers, a register function to assign functions to indices of the list corresponding to the GPIO pins, and a dispatch mechanisms which calls the correct functions when an interrupt occurs. The issue arises in the dispatch function in Listing 7.1.

```c
static void GPIOINT_IRQDispatcher(uint32_t iflags) {
  while(iflags) {
    // Utility for iterating through all active interrupt signals
    uint32_t irqIdx = GPIOINT_MASK2IDX(iflags);
    // Mark interrupt as handled
    iflags &= ~(1 << irqIdx);
    // Check if the interrupt has a callback
    if (gpioCallbacks[irqIdx]) {
      // Call the callback
      gpioCallbacks[irqIdx](irqIdx);
    }
  }
}
```

Listing 7.1: GPIO Dispatcher from `emlib`

A first take at porting the dispatcher function to `Rust` yields the code in Listing 7.2. It is quite easy to see that the mutable global state is read twice exposed by the compiler requirement to include the `unsafe` keyword (lines 10 and 15). This means that there is a possibility of the second reference to return a different value than the first. For instance, the function `GPIOINT_CallbackUnRegister(uin32_t pin)` will set the function pointer in the array to `0x0` for the specified pin. If this function is called inside an interrupt handler, and this interrupt is triggered while the GPIO driver is dispatching an interrupt, the function pointer can be set to `0x0` between the check (at line 10) and the call (at line 15). Calling a function pointer that points to `0x0` will cause a `HardFault`.

```
static mut GPIO_CALLBACKS: [Option<Fn(u8)>; 16] = [None; 16];

fn dispatcher(iflags: u32) {
  while(iflags) {
    // Utility for iterating through all active interrupt signals
    let irq_idx = mask_to_index(iflags);
    // Mark interrupt as handled
    iflags &= !(1 << irq_idx);
    // Check if the interrupt has a callback
    if (unsafe { GPIO_CALLBACKS[irq_idx] }.is_some()) {
      // Window of opportunity

      // Unwrap the callback and call the function
      unsafe { GPIO_CALLBACKS[irq_idx] }.unwrap()(irq_idx);
    }
  }
}
```

Listing 7.2: GPIO Dispatcher naively ported to Rust

7.1.2 Analysis of Assembly

To dive a bit further into the issue and to prove that it is only present at optimization level O0 we consider the assembly code, generated by compiling the C source, for the dispatcher function. The subsection of the GPIOINT_IRQDispatcher in assembly generated by arm-none-eabi-gcc -O0 -S is reproduced in Listing 7.3.

```
GPIOINT_IRQDispatcher:
  ;; ...                     ;;
  ldr r3, .L34               ;; r3 = gpioCallbacks
  ldr r2, [fp, #-8]           ;; r2 = irqIdx
  ldr r3, [r3, r2, asl #2]    ;; r3 = gpioCallbacks[irqIdx]
; start interrupt window     ;;
  cmp r3, #0                 ;; if (r3 == 0) {
  beq .L30                   ;;
  ldr r3, .L34               ;;    r3 = gpioCallbacks
  ldr r2, [fp, #-8]           ;;    r2 = irqIdx
; end interrupt window       ;;
  ldr r3, [r3, r2, asl #2]    ;;    r3 = gpioCallbacks[irqIdx]
  ;; ...                     ;;
  bx  r3                     ;;    (*r3)();  call the function
  ;; ...                     ;; }
```

Listing 7.3: GPIOINT Dispatcher in assembly with O0

Here we see a window of 4 instructions where the proposed harmful interrupt can occur. It is the `ldr` instruction just before the window opening and the one just after that causes the issue. These two loads must load the same address for the logic to be valid, although the second one is just required to not load `0x0` in order not to cause a `HardFault`. If we look at the same assembly generated by compiling the code with `arm-none-eabi-gcc -O1 -S` in Listing 7.4, we see that the issue has been eliminated.

```
GPIOINT_IRQDispatcher:
  ;; ...                     ;;
  ldr r5, .L5                ;; r5 = gpioCallbacks
  ;; ...                     ;;
  and r3, r0, #255           ;; r3 = irqIdx
  ;; ...                     ;;
  ldr r3, [r5, r3, asl #2]   ;; r3 = gpioCallbacks[irqIdx]
  cmp r3, #0                 ;; if (r3 == 0) {
  ;; ...                     ;;
  bxne    r3                 ;;    (*r3)()
  ;; ...                     ;; }
```

Listing 7.4: GPIOINT Dispatcher in assembly with O1

At O1 the compiler has performed Common Subexpression Elimination (CSE) to remove the duplicate load present in Listing 7.3. This can be eliminated with the assumption that the `gpioCallbacks` will not be changed by any external code. But as the `Rust` version in Listing 7.2 suggests this code can lead to a *data race* because it is referencing a global mutable variable.

7.1.3 Proposed solution

The solution to this problem is quite straightforward by performening the CSE manually. Listing 7.5 contains the implementation proposed to Silicon Labs to resolve this issue.

```
static void GPIOINT_IRQDispatcher(uint32_t iflags) {
  while(iflags) {
    uint32_t irqIdx = GPIOINT_MASK2IDX(iflags);
    iflags &= ~(1 << irqIdx);
    GPIOINT_IrqCallbackPtr_t callback = gpioCallbacks[irqIdx];
    if (callback) {
      callback(irqIdx);
    }
  }
}
```

Listing 7.5: GPIOINT Dispatcher without data race

We again consult the generated assembly code, given in Listing 7.6, to verify that this resolved the issue at all optimization levels.

```
GPIOINT_IRQDispatcher:
  ;; ...                       ;;
  ldr   r3, .L34               ;; r3 = gpioCallbacks
  ldr   r2, [fp, #-8]          ;; r2 = irqIdx
  ldr   r3, [r3, r2, asl #2]   ;; r3 = gpioCallbacks[irqIdx]
  ;; ...                       ;;
  cmp   r3, #0                 ;; if (r3 == 0) {
  ;; ...                       ;;
  bx    r3                     ;;    (*r3)()
  ;; ...                       ;; }
```

Listing 7.6: GPIOINT Dispatcher for proposed solution at O0

7.1.4 Discussion

The issue presented in this section is a minor one and will probably never cause a `HardFault` in a real world application. Nevertheless, it serves as an example of how the `unsafe` keyword in `Rust` makes the programmer think twice about the code in these unsafe sections.

This discussion also points to the gains that can be achieved by using `Rust` to prototype subsets of a `C` library. It can be interesting to see if more issues like this one will arise, just by introducing the patterns and constructs from the `Rust` language and the strict `rustc` compiler.

7.2 Handling interrupts with Closures

This section describes an experimental approach to handling interrupts with closures. The motivation for using this pattern is to make the code more `Rust` idiomatic and to make use of the ownership rules applied to closures. The `Rust` programming language frowns upon using global variables, especially when the variables are mutable. Using such variables forces the programmer to use unsafe blocks, thus transferring the responsibility of the safety analysis from the compiler to the programmer. Therefore, avoiding mutable global state is a goal of any `Rust` program.

7.2.1 Motivation

Let us consider a simple example for motivating the use of closures to handle interrupts. The example application samples an analog signal and saves the result to a memory buffer. An example of such an application is an audio filter, which samples an audio input connected to the ADC and stores a window of samples in RAM for further processing.

```rust
// Declaring a Circular Buffer Type globally
const N: usize = 1024;
static mut IDX = 0;
static mut BUFFER: [u32; N] = [0; N];

fn main() {
  let adc = adc0();
  // Using BUFFER requires unsafe
  // e.g.: unsafe { &BUFFER[..] }
  loop { /* ... */ }
}
pub extern fn ADC0_IRQHandler() {
  let adc = adc0();
  let sample = adc.get_single_data();
  // Writing to the buffer is considered unsafe
  unsafe { BUFFER[IDX % N] = sample; IDX += 1; }
}
```

Listing 7.7: Analog sampler with global buffer

Listing 7.7 shows the proposed example with a conventional interrupt handler. The interrupt handler is in the global scope, so it can only access global variables and therefore the buffer must be declared as `static mut`. This require all read and writes to the buffer to be handled within `unsafe` blocks. A huge restriction on variables defined in the global scope in `Rust`, is that they can only be of types which has constant-expression constructors. This is a fact which we praised in Section 3.1, as it provides a very simple startup procedure, but it limits the datatypes which can be shared between interrupt handlers and the rest of the code.

```rust
fn main() {
  let mut adc = adc0();
  let buffer = CircularBuffer::new();
  let mut ch = buffer.in();
  // Register a closure on the ADC. The closure will be called each
  // time a new sample is ready with the sample as an argument. The
  // 'move' keyword is used to move ownership of the 'ch' variable.
  adc.on_single(move |sample| ch.send(sample));

  // Reading from buffer is safe
  // e.g.: &buffer[..];
  loop { /* ... */ }
}
```

Listing 7.8: Analog sampler with local buffer

In Listing 7.8 we present an example implementation using a closure as an interrupt handler. The global state is now replaced with a buffer that is owned by the `main` function stack frame. In this discussion, we consider the main stack frame, the stack frame for the `main` function, to be a special frame. This comes from the fact that the `main` function contains an infinite loop causing it to never terminate, and the frame will not get deallocated. On a bare-metal system, this is true as long as a fatal error does not occur. So we can rely on variables owned by the main stack frame to live for the duration of the application. This ensures that the `buffer`, for practical purposes, has the same lifetime as the `BUFFER` from Listing 7.7, but because the variable is not a `static mut`, it lets the programmer avoid `unsafe` blocks and let the compiler ensure safety.

One implementation detail here is the imagined `CircularBuffer` type. The type is based on the same principle as the `Rust` standard library `channel` type, which provides a facility for interprocess communication. The channel has one *read end* and one *write end* enabling the producing process to send a stream of messages to the consuming process. This is required for the ADC callback to be able to write to the buffer while the main function retains ownership of the buffer. In the example the `in` function creates the *write end* of the circular buffer.

The core of this example is the line `adc.on_single(move |sample| ch.send(sample));`. This creates a closure that takes ownership over the *write end* for the circular buffer. The closure is passed as an argument to the `on_single` method on the ADC ensuring that the closure is called each time a new sample is ready with the sample as an argument.

7.2.2 Implementation

This section looks at how we built an abstraction for exposing the behavior that was presented in the previous section. The implementation shows how we can use the `unsafe` keyword to build this safe abstraction. As we desribed in Section 2.1.7, by using this keyword we take on the responsibility of ensuring that our code satisfies the invariants the compilers safety analysis is built on. Because of this, we include a discussion of what makes the building blocks we use here `unsafe` and how we can verify that the final abstraction is safe to use.

The process of handling an interrupt was described in Section 3.2. In short, a public function with a specific name handles the corresponding interrupt. To implement the pattern above, we need to get the globally defined interrupt handler `ADC0_IRQHandler` to call a closure created in the `main` function.

As already discussed, the interrupt handlers can only access global variables, which requires us to store the closure value in a static variable. We can not do this directly because closures do not have static initializer functions, thus, we need to use raw pointers. Listing 7.9 shows what a raw pointer to a closure looks like in `Rust`, note that we put the pointer inside an `Option` to avoid using a null pointer.

```
static mut CLOSURE: Option<*const Fn()> = None;
```

Listing 7.9: Storing a raw pointer to the closure globally

This `CLOSURE` variable is unsafe to use because it is a static mutable variable. Listing 7.10 shows a safe abstraction to register and dispatch events with this handle. Notice how the responsibility of handling the ownership of the closure is transferred from the compiler to the programmer in the `unsafe` block in the `register` function. This is done with the `from_raw` and the `into_raw` functions, which converts between *managed* and *raw* pointers. Respectively, these functions tell the compiler to start and stop the borrow-checker for the pointer that is returned from the two functions.

```rust
// Registers an interrupt handler
fn register(f: Box<Fn()>) {
  unsafe {
    // Deallocate old handler if existing
    if let Some(old) = CLOSURE {
      // Remove the global reference
      CLOSURE = None;
      // Return the ownership of the pointer to a managed Box.
      // This transfers the responsibility of deallocating the
      // closure back to the compiler.
      let _ = boxed::Box::from_raw(old);
      // Omitting the above line will not trigger compilation
      // error, but the old closure value will be leaked.
    }
    // Consume the Box pointer and return a raw pointer to the
    // closure. This transfers the responsibility of deallocating
    // the closure from the compiler to the programmer
    let raw = boxed::into_raw(f);
    // Save the closure pointer in the global reference
    CLOSURE = Some(raw);
  }
}
// Dispatch an event by calling the closure if it is registered
fn dispatch() {
  // The closure is stored in a global mutable variable,
  // so the access to this variable is unsafe
  unsafe {
    // Unwrap the closure value
    if let Some(func) = CLOSURE {
        // The closure is stored behind a pointer which must
        // be dereferenced, it is called with its environment
        // by invoking the 'call' function
        (*func).call(())
    }
  }
}
```

Listing 7.10: Safe abstraction over global raw pointer

The above listing use `unsafe` code in order to provide a safe abstraction to interact with the globally stored closure. The functionality is described throughout the comments. In the listing, we see all of the three operations which were defined as `unsafe` in Section 2.1.7. These are mutating a static mutable variable (the `CLOSURE`), calling unsafe functions (`into_raw` and `from_raw`), and dereferencing a raw pointer (the `func` variable in the `dispatch` function). The `unsafe` functions deal with transferring the ownership of the heap allocated pointer from the compiler, to the callee, and back to the compiler. If these functions are used improperly, it can lead to different memory related problems like double-free, use-after-free, and memory leaks. Dereferencing the `func` pointer is considered unsafe because it might point to invalid memory, the `register` function makes sure that this pointer is valid.

Listing 7.11 implements the interface that was presented in Listing 7.8 for the ADC, by utilizing the `register` and `dispatch` functions from Listing 7.10. Notice that the implementation detail of the `unsafe` blocks in the `register` and `dispatch` functions does not affect the user of the abstraction.

```rust
impl Adc {
  // This constructor is defined in ‘emlib’
  pub fn adc0() -> &'static Adc { /*...*/ }
  pub fn on_single(&'static self, callback: Box<Fn(u32)>) {
    // Make sure the callback for a single conversion is enabled
    self.int_enable(IEN_SINGLE);
    // Call the utility to register an interrupt handler.
    // The ‘move’ keyword is used to move ownership of
    // the callback function into the closure
    register(Box::new(move || {
      // Clear the interrupt signal to mark it as handled
      self.int_clear(IF_SINGLE);
      // Call the interrupt handler with the ADC sample
      callback(self.data_single_get())
    }));
  }
  // Clears interrupt signals
  pub fn int_clear(&self, flag: u32) { /*...*/ }
  // Triggers an ADC conversion and returns the result
  pub fn data_single_get(&self) -> u32 { /*...*/ }
}
// The ADC0 Interrupt handler
// This is defined as a part of the library
#[allow(non_snake_case)]
fn ADC0_IRQHandler() {
  dispatch();
}
```

Listing 7.11: ADC abstraction over an Event Hub

As discussed in Section 3.2, the `Gecko` provides a vector of interrupt handlers. To minimize the boilerplate code for this method, the registering and dispatch mechanisms are implemented as part of an *event hub* in the actual library. This hub contains a map from event, corresponding to the interrupt names, to the interrupt handler closure. We have left out the implementation of the event hub in this section, in order to focus more on explaining how we have handled the ownership of the closures.

7.2.3 Discussion

The method for handling interrupts with closures discussed in this section provides a nice facility to use idioms that are common in `Rust` code. They proved a means to avoid explicit use of `unsafe static mut` variables and, as we showed in Listing 7.11, let us build higher level abstractions. We revisit this section as part of a larger discussion concerning *ownership to hardware* in Section 9.2.

7.3 Rust Embedded Modules

This section describes a separate project, which we refer to as REM. REM have been developed alongside the various binding libraries, and it contains a couple of higher-level modules for the different peripheral bindings that are part of the `RustyGecko` platform.

We have looked to other projects like `Zinc`, `arduino`, and ARM `mbed` for inspiration to this library. The peripheral abstractions that have been implemented as part of REM are still in very early development, and most of them are not yet general enough to be adapted to all new projects.

7.3.1 USART

The USART have many different use-cases. It is a peripheral that is used for transferring of data, but it is also a very convenient tool to use for simple debugging of programs. It can be used to send single strings of text between a PC and the MCU, which is convenient for “println”-debugging, and it is a good tool for defining Command Line Interface (CLI) programs.

The `Gecko` has a total of three different USARTs which can be configured to run on a total of eleven different locations (i.e. GPIO Ports and Pins). If the GPIO configuration for a USART is not specified correctly, the peripheral will not function correctly either. The goal of the USART abstraction was to make it easy to initialize the peripheral, as well as providing simple methods to read and write strings, and transfer data between two end-points.

The `Usart` module has an initialization procedure that takes care of initializing its required GPIO pins based on a specified location. This is similar to the approach made by `Zinc`, but instead of failing with a compilation-error if it is incorrectly configured, as in `Zinc`, it will fail at run-time. A minimal example that shows how to initialize a USART, and send and receive strings, is shown in Listing 7.12. Note that the example is simplified slightly, we have trimmed away some `extern` and `use` statements to make the important parts clearer. The point of this example is to demonstrate a program that initializes and uses a USART with only four lines of code.

```rust
extern crate emlib;   // Include 'emlib' bindings
extern crate modules; // Include 'REM'
use modules::Usart;   // The Usart module

fn main() {
  // Acquire a USART with default configuration...
  let mut usart: Usart = Default::default();
  // ... and initialize its GPIO.
  usart.init_async();

  loop {
    // Perform a blocking read operation...
    let name = usart.read_line();
    // ... and echo back with a nice message.
    usart.write_line(&format!("Thank you, {}!", name));
  }
}
```

Listing 7.12: Example usage of REM's USART module

7.3.2 GPIO

The GPIO peripheral are used extensively as a dependency for many other peripherals throughout `emlib`. The microcontroller's CPU pins are configurable as GPIO, all these pins are ordered into ten ports (Port A - Port H) with up to 16 pins each (Pin 0 - Pin 15). The pins can be configured individually to be used as input, output, or both, to the MCU.

The GPIO module in REM consists of a `GpioPin` structure, and two traits for `Button`'s and `Led`'s, respectively. The `GpioPin` is an abstraction on top of `emlib`'s GPIO definition, and the two traits implements a few convenient methods that abstracts away the underlying `GpioPin`. An example that shows how to initialize and use a button and a LED on the `STK` is shown in Listing 7.13. Notice from the code that we only ever interfere directly with the two traits, and that we do not care about the underlying `GpioPin`, apart from when we define the button and the LED.

It is important to note the *current* limitations of this module. The two implemented traits provides an intuitive abstraction layer for their purposes, but GPIO in general, is so much more than just buttons and LEDs. The module was first developed for buttons and LEDs because they are easy to interface with, but it will require some alteration to be more 'general purpose'.

```rust
extern crate emlib;    // Include 'emlib' bindings
extern crate modules;  // Include 'REM'
use emlib::gpio::Port;
use modules::{GpioPin, Button, Led};
// Define a button and a LED. The 'static lifetime tells
// us that BTN and LED are alive for the whole program
const BTN: &'static Button = &GpioPin { port: Port::B, pin: 9 };
const LED: &'static Led    = &GpioPin { port: Port::E, pin: 2 };

fn main() {
  // Initialize the underlying GPIO pins
  BTN.init();
  LED.init();
  // Register a callback function for the button
  BTN.on_click(blink_led);
  loop {}
}
// This function gets called when the button is pressed
fn blink_led(_pin: u8) {
  LED.toggle();
}
```

Listing 7.13: Example usage of REM's GPIO module

7.3.3 DMA

The DMA peripheral on the `Gecko` is used for transferring data from one location to another, without intervention from the CPU. The interface to the DMA provided by `emlib` is a low-level API, which deals with hardware descriptors and raw pointers for controlling the DMA. Here we look at a higher level abstraction over the DMA module, which considers devices and buffers and the specification of the flow between these devices.

The core of the approach defines two types of endpoints which can be interacted upon with DMA, *readable* and *writable*. In this classification, an ADC is readable as it produces samples and, the DAC is writable as it can consume samples. A USART fits both descriptions; this is because data can both be written to and read from the peripheral. Both descriptions do also apply to memory allocated buffers.

These abstractions are modeled by providing the two traits, `Readable` and `Writable`, as shown in Listing 7.14. It is important to note that, even though the two traits define the *same* methods, they have a *semantic* difference.

```rust
trait Readable {
  fn as_ptr(&self) -> *mut c_void; // Base pointer to device
  fn inc_size(&self) -> DataInc;   // Increment in bytes
  fn size(&self) -> DataSize;      // Element size in bytes
  fn n(&self) -> Option<u32>;      // Number of elements to transfer
}
trait Writable {
  fn as_ptr(&self) -> *mut c_void;
  fn inc_size(&self) -> DataInc;
  fn size(&self) -> DataSize;
  fn n(&self) -> Option<u32>;
}
```

Listing 7.14: Traits used for DMA transfers

Both traits defined in Listing 7.14 requires the same set of methods. These methods are required by the underlying DMA implementation and are described in the `emlib` documentation for DMA [16]. As mentioned, both traits can be applicable for some peripherals, and this demonstrates `Rust`'s facility to do method resolution when a type implements multiple traits that can result in function name collisions.

Listing 7.15 shows an example of using the DMA abstraction to transfer samples from the ADC to RAM. The `start_basic` function relies on the two traits to set up the hardware specifiers with the low-level API. Both the `Readable` and `Writable` traits are implemented for the memory buffer. In this use case, the type of the `dst` parameter in the `start_basic` function ensures that the correct implementation is chosen.

The DMA abstraction described here is only implemented for the simplest DMA transfers from the `emlib` DMA API. The `emlib` API provides more complex facilities (e.g. scatter-gather) which can cause the interfaces to change if they are to be supported. However, there exists facilities for registering closures to handle reactivation of long running DMA transfers; the closure will be called on the interrupt signal given by the DMA controller when the transfer is finished. This facilitates a programming model which is similar to the one presented in Section 7.2.

```rust
// Create a static RAM buffer
static mut BUFFER: [u8, 4] = [0; 4];

fn main() {
  // Initialization omitted. Assume instead
  // that ‘adc0’ and ‘dma0’ hold references to the peripherals

  // Start a DMA transfer from the ADC to RAM
  dma0.start_basic(
    &adc0,                    // The ‘adc0’ implements ‘Readable’
    unsafe { &mut BUFFER }, // The RAM buffer implements ‘Writable’
    AdcSingle                 // Reference to the interrupt signal
  );
  loop {}
}

// The signature for the start_basic is included for the discussion
impl Dma {
  pub fn start_basic(&mut self,
                     src: &Readable, dst: &Writable, on: Signal);
}
```

Listing 7.15: DMA transfer utilizing the trait abstractions

7.4 Projects

This section describes two applications that were developed as part of the evaluation process of the RustyGecko platform. The two applications have been implemented in both Rust and C, and we have gathered results from energy measurements, code size, and execution performance for all of the applications. We use these findings to give a qualitative evaluation of Rust for a bare-metal system. The results are presented in Chapter 8 and discussed in Chapter 9, respectively.

7.4.1 Project I - Sensor Tracker

The Gecko is well suited for applications that focus on low energy consumption. Examples of such applications are wearable devices, like the fitbit[1] activity tracker.

The following sections describes an interrupt driven sensor application that was developed for the STK, we refer to this application as the SensorTracker. The

[1]https://www.fitbit.com/

project has an emphasis on low energy consumption and it uses sleep modes to save energy during execution.

Goal

The `SensorTracker` application was developed to compare the `Rust` and `C` languages against each other, with an emphasis on energy consumption on a bare-metal system. An energy efficient application is largely concerned with performing its task quick and going to sleep. Different parts of the `Gecko` gets switched off, depending on the sleep mode the chip is in, and the key to low power consumption is to do as much of the data processing at the lower sleep modes.

Requirements

The requirements for the `SensorTracker` application are summarized in Table 7.1. We wanted the application to demonstrate the usage of a wide range of sensors; the required peripherals are available on the two given boards in **ST1**. The sensors from **ST2** were chosen to be the internal temperature sensor on the `Gecko`, and the humidity sensor and the external temperature sensor that are available on the `BIO-EXP`. **ST3** and **ST4** was chosen because they demonstrate two different use-cases for the `SensorTracker`. The first mode demonstrates a self-contained system that collects data, and the second mode shows that the application can be used to provide data to external devices.

Requirement	Description
ST1	The application should be made for the `STK` and utilize the `BIO-EXP` for additional sensors.
ST2	The application should collect *samples* of temperature and humidity from various peripherals at timed intervals.
ST3	The samples should be collected and stored internally in the `Gecko`'s RAM.
ST4	The sample data should be made available to an external application with the USART.

Table 7.1: Requirements for the `SensorTracker`

Implementation

The application has two modes of operation, sample collection and sample transfer. The buttons on the `STK` are used to switch between the two operation modes of the `SensorTracker`, these modes are shown in Table 7.2, and described in the paragraphs below.

Current Mode	**Button Pressed**	**Action**
Collect	PB0	Go to Transfer
Collect	PB1	Stay in Collect
Transfer	PB0	Stay in Transfer
Transfer	PB1	Go to Collect after current transfer

Table 7.2: Operation modes for the `SensorTracker`

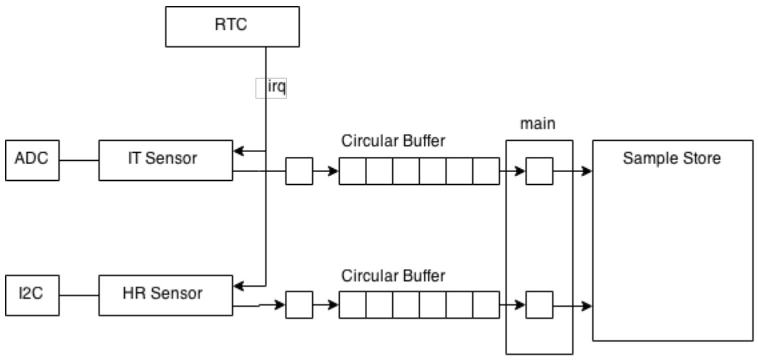


Figure 7.1: Sample collection phase

Sample Collection The main part of the application, which consists of gathering the samples, was implemented as described in Figure 7.1. The RTC clock is set up to generate interrupts each n milliseconds. On each interrupt, a new sample is created by the sensors and pushed into a circular buffer structure. The main loop, which is executed once after each interrupt has been handled, extracts all the sample currently in the circular buffer and stores them in RAM.

The sensors[2] used in the application are shown in Table 7.3. We can see from this table that two additional peripherals need to be configured for the `SensorTracker`, for the sensors to work properly. The ADC is used to convert the internal temperature to a digital value, while the external sensors available on the `BIO-EXP` is retrieved via the `Gecko`'s I^{2}C interface.

#	**Name**	**Connection**	**Measured Data**
0	Internal Temperature	ADC0	CPU Temperature
1	Humidity Relative	I2C1	Room Humidity
2	Temperature	I2C1	Room Temperature

Table 7.3: Sensors used by the `SensorTracker`

[2]Sensor #1 and #2 are the same sensor, but they are exposed as two different ones by the application.

Connecting to the STK We use a PC to interface with the `Gecko` over USART when the application is in Transfer mode, and the application can then be controlled via a CLI. We have used a USB cable with an FTDI chip[3] to connect with a USART on the `STK`. Figure 7.2 shows how the RX (green), the TX (white), and Ground (black) wires are connected. The application can then be interacted with, with a terminal application like `picocom`[4]. Connecting to the device with baudrate 9600 and error correction set to 8-1 (the defaults of `picocom`) will provide access to the `SensorTracker` CLI.

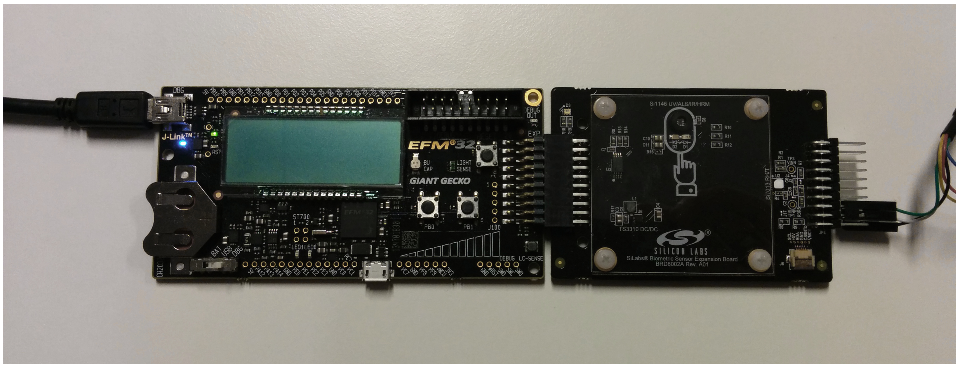
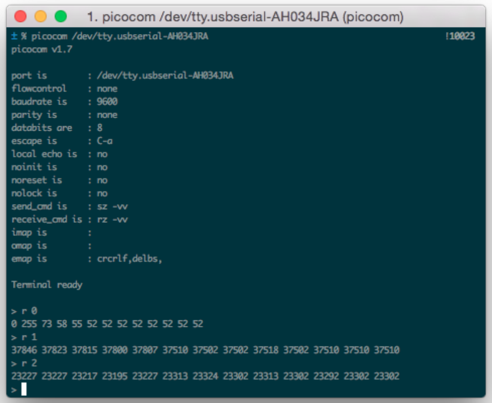


Figure 7.2: Connecting to the `STK`

Command Line Interface The CLI of the application contains only a single command; read. The read command takes one argument, and it is on the format `r n`, where n is the integer 0, 1 or 2. The command is terminated with a carriage return (i.e. the ASCII symbol `\r`). All non-conforming commands are ignored by the application. The n parameter is used to select one of the sensors that was presented in Table 7.3. Every time a conforming command is sent to the application, it will respond over USART with all the data that have been collected by the selected sensor. A screenshot over how program interaction with the `SensorTracker` looks like is shown in Figure 7.3.

[3]Future Technology Devices International provides chips for serial to USB conversion
[4]`picocom` is a serial terminal commonly found in many Unix-like systems



```
1. picocom /dev/tty.usbserial-AH034JRA (picocom)
± % picocom /dev/tty.usbserial-AH034JRA                                    !10023
picocom v1.7

port is        : /dev/tty.usbserial-AH034JRA
flowcontrol    : none
baudrate is    : 9600
parity is      : none
databits are   : 8
escape is      : C-a
local echo is  : no
noinit is      : no
noreset is     : no
nolock is      : no
send_cmd is    : sz -vv
receive_cmd is : rz -vv
imap is        :
omap is        :
emap is        : crcrlf,delbs,

Terminal ready

> r 0
0 255 73 58 55 52 52 52 52 52 52 52 52
> r 1
37846 37823 37815 37800 37807 37510 37502 37502 37518 37502 37510 37510 37510
> r 2
23227 23227 23217 23195 23227 23313 23324 23302 23313 23302 23292 23302 23302
>
```

Figure 7.3: Example run of Command Line Interface

7.4.2 Project II - Circle Game

This section describes the implementation of a game that was developed for the `DK`. The game is simple, but CPU intensive, and was developed as a part of measuring the performance of `Rust` on the `Gecko`.

Goal

The `CircleGame` application was developed to compare the performance between `Rust` and `C`. It is not easy to give a performance metric, and compare two languages directly against each other based on only one application like this. However, an application like this gives us a good indication of whether the two languages differ or have roughly the same performance.

Requirements

The requirements that were made for the game are summarized in Table 7.4. **CG1** and **CG2** sets the hardware requirements for the application; we chose to restrict it to the `DK` because of its on-board LCD screen and header pins. The two modes mentioned in **CG3** was deemed necessary for testing purposes and for measuring performance, respectively. **CG4** specifies the performance metric, FPS was chosen because it is an intuitive way of measuring performance. The result will be a number that represents how many iterations of the game's main loop have been executed each second.

Requirement	**Description**
CG1	The game should be made for the `DK`.
CG2	The graphics should be rendered on the LCD screen.
CG3	The game should support two modes, it should be controlled with a gamepad, or be self-playable.
CG4	The performance should be measured in the number of FPS.

Table 7.4: Requirements for the `CircleGame`

Description

The game was first written in `C` by one of our supervisors as part of the TDT4258 [5] course at NTNU, and later ported by us to `Rust`. It is a simple game that consists of three components that are drawn to the screen; two circles and an obstacle. The two circles can be controlled with a gamepad that is connected to the `DK`'s header pins, Figure 7.4 shows a setup of the game. The obstacle is randomly generated and has either one or two gaps, it spawns on top of the screen and is moved down one step for every iteration of the game loop. The goal of the game is to avoid any collision between the circles and the obstacle. If the obstacle reaches the bottom of the screen without colliding with any of the circles the game score is increased. However, if any of the circles collide with the obstacle, the game is over, and the score is reset to 0.

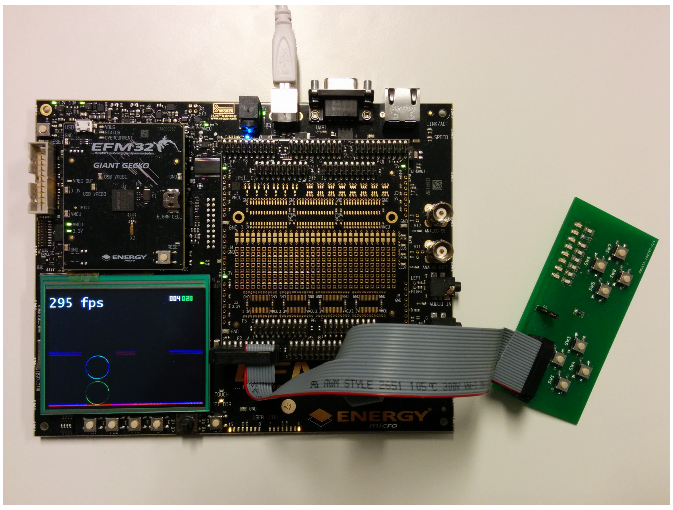


Figure 7.4: `CircleGame` running on the `DK` with the attached gamepad

[5] `http://www.ntnu.edu/studies/courses/TDT4258`

The game consists of three phases; initialization, reset, and the game loop. Pseudo code for the game is shown in Listing 7.16, as the code suggest, most of the work is done in the game loop. We calculate the FPS for the game by increasing a counter for every iteration of the loop. An interrupt is also set up to be triggered once every second, which consecutively updates the FPS and resets the counter.

The game also has support for playing by itself. This mode is necessary because the optimized versions of the game run with several hundreds of iterations each second, and it makes it easier to collect the results from the performance test.

```
static mut FRAME_COUNT = 0;
static mut LAST_FRAME_COUNT = 0;

fn main() {
  init();  // Run Microcontroller initialization
  reset(); // Reset the Game Environment
  loop {   // Game Loop
    let input = get_user_input(); // Get input from user buttons
    player.move(input);           // Move Player according to input
    obstacle.move();              // Move obstacle
    // Check if collision occurred
    if check_collision(player, obstacle) {
      game_over(); // Report game is over to player
      reset();     // Reset the Game Environment
    }
    redraw_screen(); // Update contents on the LCD
    FRAME_COUNT += 1;
  }
}
// Interrupt handled once each second
extern fn SysTick_Handler() {
  LAST_FRAME_COUNT = FRAME_COUNT;
  FRAME_COUNT = 0;
}
```

Listing 7.16: Pseudo code of the `CircleGame`

Chapter 8

Results

In this chapter, we present the results after conduction measurements of the applications written for the `RustyGecko` platform. We focus mainly on the `SensorTracker` and `CircleGame` applications but include some smaller applications to look at concepts in isolation. The three metrics chosen for measurements are as follows:

- Performance
- Energy Consumption
- Code Size

These metrics are integral to embedded computing systems and are somewhat related to each other. In the last section of this chapter, we look at how the heap allocation is performed in `Rust` and `C`.

8.1 Performance

This section describes the performance measurement of the system performed on the `DK`. The game application was implemented as described in Section 7.4.2 in both `C` and `Rust`. The performance was measured by recording FPS performance metric. This metric measures the amount of work/second, and it is simple and commonly used when measuring the relative performance of realtime graphic applications.

8.1.1 Measurement

The measurement was done by executing the application on a `DK` board and visually recording the on screen FPS, as seen in Figure 8.1. The recorded number was gathered by letting the application run past the initialization loop and waiting for the metric to stabilize. When the FPS was stable, the lowest and the highest number reached within a 5 second time-period was sampled. The mean of the two samples is presented in the results below. The largest variance in the presented samples were 5 FPS. This process was repeated on two different `DK` boards.

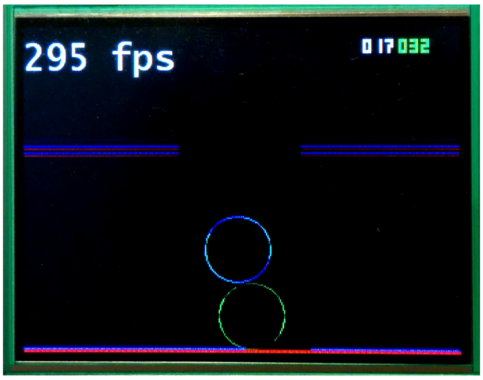


Figure 8.1: The on screen FPS on the `DK`

8.1.2 Measurement Bias

When measuring performance, one has to consider a number of biases that can occur while performing the measurement. A bias is an arbitrary external noise that might distort the result of the measurements. Some of these biases can and should be eliminated before measuring, while others are harder or impossible to remove.

The following biases were found when analyzing the game application:

User Input
The game application was developed as a human playable game. When measuring performance, deterministic results are preferable. This bias was removed by implementing a simple deterministic artificial intelligence which emulates the user input.

Random Number Generator
A Random Number Generator (RNG) is used to generate a stream of seemingly random numbers. To avoid performance impacts from the different RNG implementations for `C` and `Rust`, a simple deterministic RNG was implemented and used.

Measurement Overhead
Often when measuring the performance of an application at a course granularity, the measurement adds to the execution time. This is largely the case when measuring FPS, as it adds profiling code to the actual application, thus

affecting the performance of the application. In this experiment, we are interested in the relative performance between `C` code and `Rust` code. Therefore, the added bias by the FPS measurement is acceptable as long as it is the same for both code bases.

Optimization Characteristics
Various applications perform differently when subjected to different optimizations. This fact leads to a trade-off when deciding the level of optimization to apply to the program. To account for this bias, we look at the performance metric for all optimization levels.

8.1.3 Results

In this section, we present the results obtained when measuring performance.

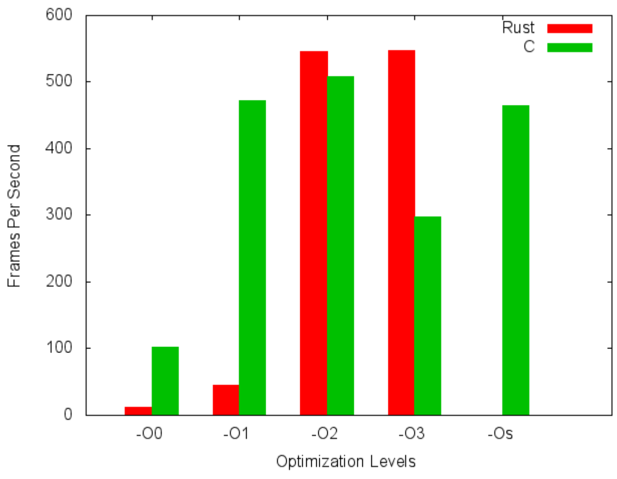


Figure 8.2: Frame/Second achieved by `Rust` and `C` code

Figure 8.2 graphs the results for the performance measurements. The Y-axis shows the number of Frames Per Seconds achieved by running the game on the optimization level given by the X axis. We see that the `C` code is ˜10x faster on O0 and O1, but `Rust` equates by providing a 1.07x speedup over `C` at O2. `C` achieves the best performance at level O2 while `Rust` is slightly faster on O3 compared to O2. Our brief analysis of this suggests that some of the high-level abstractions in `Rust` are fairly inefficient without optimizations. An example of these abstractions is the `Iterator`-based `for` loop, which is used extensively throughout the `CircleGame` application.

The poor performance for the O3 optimization level for the `C` was unexpected. To further investigate this issue, we first considered the instruction cache hit ratio for the O3 and O2 binaries. We did not find an explanation in the results, as the hit ratios were close to equal.

The optimization levels considered here, defines a set of individual optimizations which can be activated or deactivated by passing flags to the compiler. Next we, looked at the change in performance due to each individual optimization flag in the set difference of $O3 - O2$. By adding each flag, one-by-one, from the set difference to an O2 base build, we managed to identify the source of the performance degradation. The source was the `-ftree-loop-distribute-patterns` flag. This flag is used to collect common initializations of variables from different loop iterations and substitute these initializations with library routines like `memset`. We refer the reader to the `gcc` documentation [9] for further explanation of the flag. The `CircleGame` application contains a fair amount of loops with initialization code, so if this optimization for our use-case is degrading the performance, it is quite natural for the overall performance to take a big hit. For completeness; the performance of an O3 binary without the mentioned flag is equal in performance to the O2 binary for this application.

8.2 Energy Consumption

In this section, we look at the energy consumption of the `SensorTracker` application described in Section 7.4.2. The measurements was performed using the `STK` and `BIO-EXP` boards. The `SensorTracker` is an interrupt driven application and has two modes of operation from an energy consumption perspective. It turns *On* for each interrupt to perform the measurement and turns *Off* when the measuring is complete.

8.2.1 Measuring

The measurement was performed with the *Energy Profiler* application supplied by Silicon Labs as a part of their *Simplicity Studio* software suite. The profiler measures on board current at a sample frequency of 6250Hz. Power, measured in Watt (J/s), is given by the formula $P(J/s) = V * I$, where V is voltage and I is current. By accumulating the Power over time, we get the energy consumption given in *Joule*. This metric is reported by the *Energy Profiler*.

Each measurement, called a *run*, was gathered manually by executing the sample collection process (see Section 7.4.1) for 30s and recording the energy reported by the profiler. This process was repeated four times for each data point, and an average was calculated after removing the sample with the highest variance. This process was introduced to remove human error from the manual collection. The number of collected and discarded samples were based upon the stability of the results, and the largest variance in the collected samples were 0.174%.

8.2.2 Parameter

The energy consumption was recorded for the `SensorTracker`, which was configured with different workloads. The workload is dependent on how many interrupts are trigger per run, and how much work is performed during each interrupt. To vary the workload, the number of triggered interrupts were varied by configuring the length of the interval between each interrupt while the work was held constant for each interrupt. Table 8.1 gives the interrupt interval and the corresponding number of interrupts per *run* used for the measurement.

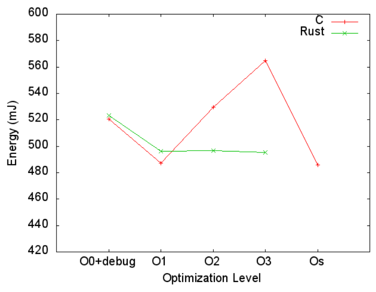
Interval	**# of Interrupts/*run***	**Execution time**
25ms	1200	30s
50ms	600	30s
100ms	300	30s
500ms	60	30s
1000ms	30	30s

Table 8.1: Interrupt Interval Parameter

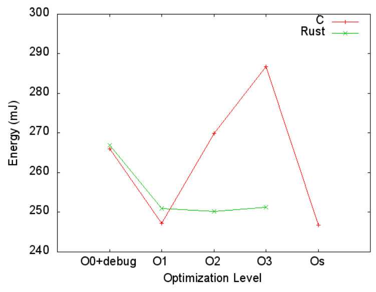
The measurement was performed at all the standard optimization levels provided by the compilers. This was done to remove the bias where different applications have better performance using different optimization levels. As noted in Section 8.3 these are *O0*, *O1*, *O2*, *O3* and *Os* (only available for `C`). As we will see in the results below, by including all the optimization levels, we uncovered another bias related to energy consumptions. The *O0* levels were only evaluated with debugging symbols.

8.2.3 Results

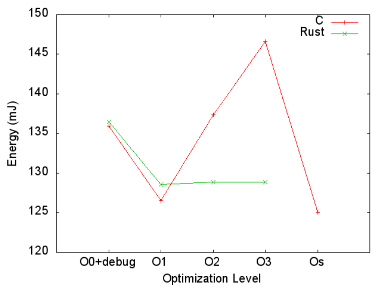
In this section, we look at the results of the energy consumption measurement. We first look at the whole picture by presenting all the measurements produced by the set of possible parameters. Later, we will consider the best configuration for `C` application together with the best configured `Rust` application for each workload.



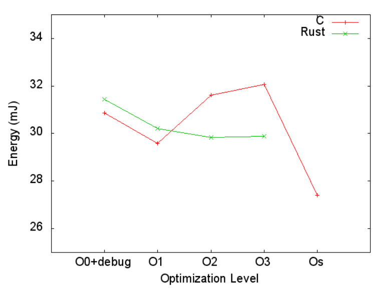
(a) 25ms



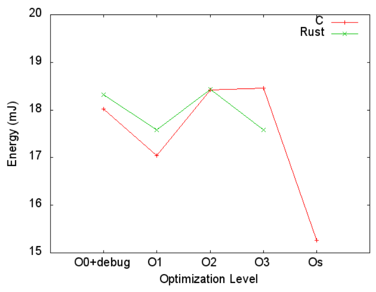
(b) 50ms



(c) 100ms



(d) 500ms



(e) 1000ms

Figure 8.3: Comparison between `Rust` and `C` for each workload

Figure 8.3 shows the energy consumption for each of the workloads and compares the optimization levels for `Rust` and `C`. We see that `Rust` and `C` have comparable consumption in each of the workload configurations. It is also evident that an external bias, investigated below, accounts for the variance between the various optimization levels.

Now we look at the relative performance comparing the version with lowest energy consumption for each workload. For the `C` code, we can easily see from Figure 8.3 that this is produced by the *Os* level. The `Rust` versions, on the other hand, are either *O1*, *O2* or *O3*, although the difference is never larger that 1%.

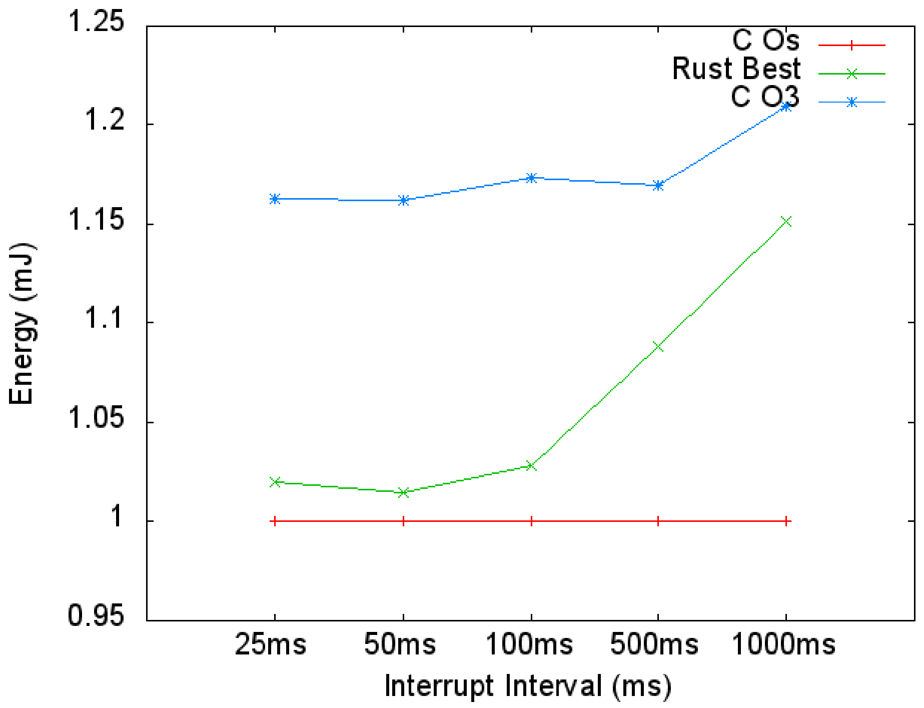


Figure 8.4: `Rust` vs `C` relative comparisons for best builds

Figure 8.4 shows the relative energy consumption by setting the consumption of the `C` *Os* build to 1 for each of the workload. The `Rust` line plots the best performing `Rust` builds relative to this `C` build. For reference, the results for the *O3* optimization level of the `C` build is included. We see that the `Rust` code always performs within ∼15% of the `C` code and is always better than the *O3* line.

The variance between the different optimization levels of `C` code in Figure 8.3 was unexpected. In this application, we anticipated that higher optimization levels would result in faster interrupt handlers and thus lower energy consumption. When the initial results did not meet this expectation, we used the *Energy Profiler* to plot the instantaneous current drawn by the application.

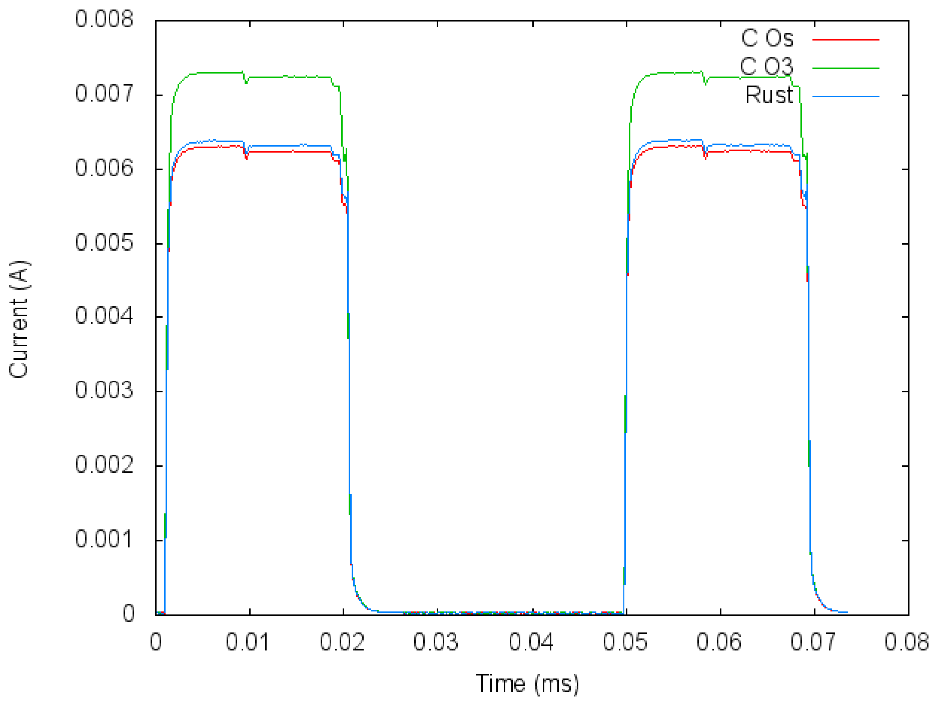


Figure 8.5: Current of 50ms workload

Figure 8.5 plots the current drawn by the `Gecko` while handling an interrupt and the idle state between interrupts. The first thing to notice about the plot is that the time it takes to handle an interrupt is constant for the various optimization levels. The second point is the difference in current drawn by the `Gecko` while handling the interrupts. We can see the O3 level draws more current compared to the Os level; we found the reason for this when we looked at the instruction cache hit ratio.

Level	**Hits**	**Misses**	**Hit Ratio**
O3	110969	43429	71.9%
Os	162029	614	99.6%

Table 8.2: Cache hit ratio for optimized `C` binaries

Table 8.2 shows the cache hit ratios recorded for binaries presented in Figure 8.5. We see that the cache hit ratio for the binary compiled with O3 has a hit ratio of ∼72% while the Os level has as high as ∼99%. The lower instruction cache hit ratio causes the `Gecko` to load instructions from flash more frequently and thus consumes more energy. This effect was not studied any closer, but can possibly be explained by the O3 level producing code which is to large for the instruction cache to contain.

8.3 Code Size

This section looks at the size of the compiled binaries for three `Rust` programs. These programs are the two projects, `SensorTracker` and `CircleGame`, and a Minimal Main program. A comparison between functionally equivalent programs in `C` and `Rust` are provided.

Code size is an important factor in an embedded system. The systems are more restricted than conventional systems, especially when it comes to storage. For the EFM32 line of microcontrollers the code is stored in flash memory. In Section 2.3, we showed that the flash memory in the EFM32 family of microcontrollers ranges from 4KB to 1MB. As Section 2.6.3 explains, the flash memory should not only contain the program code but also the constant data defined in the program. This limits the code size even further.

Another concern that makes code size a priority in embedded system is price. When putting embedded systems into production, the volume of microprocessors are usually large. Moreover, as the size of the flash correlates with the price of the microprocessors, being able to choose a smaller version can save large amounts of money.

Each program was compiled with optimization levels O0, O1, O2, and O3, and the O0 level was compiled both with and without debugging symbols. Compiling executable programs results in an `elf` binary file. The size was calculated by executing the `arm-none-eabi-size` program.

8.3.1 Measuring Size

The `arm-none-eabi-size` program accepts an `elf` binary as argument. The program then reads the file and reports the size of the **.text**, **.data** and **.bss** segments described in Section 2.6.2.

8.3.2 Parameters

The various files were compiled by setting the compiler optimization flags in the `Cargo.toml` file. The parameters used are shown in Table 8.3 with their effects.

Parameter	**Values**	**Effect**
`debug`	true, false	Sets the `-g` flag on the compilers
`debug-assertions`	true, false	A way to remove assertion statements
`opt-level`	0, 1, 2, 3	Sets the optimization flag on the compilers
`lto`	true, false	Sets the LTO flag on the linker

Table 8.3: `Cargo.toml` parameters and their effects

Each program in this section is compiled with 6 different settings, as given by Table 8.4.

Parameter	**1**	**2**	**3**	**4**	**5**	**6**
`debug`	true	false	false	false	false	false
`debug-assertions`	true	false	false	false	false	false
`opt-level`	0	0	1	2	3	3
`lto`	false	true	true	true	true	true
(c code Os)	false	false	false	false	false	true

Table 8.4: Compilation settings

For each of the optimization levels the underlying `C` sources are compiled at the same level as the `Rust` code. Notice that for the 6th optimization setting, the underlying `C` sources are compiled with the Os flag, while the `Rust` sources are compiled at O3.

8.3.3 Binary Sizes

This subsection considers the code size of programs. Functionally equivalent versions were written in both `Rust` and `C`, and here we compare the size of the binaries produced at each optimization level presented in Table 8.4. Figure 8.6 presents the sizes of the generated binaries for the two projects described in Section 7.4.

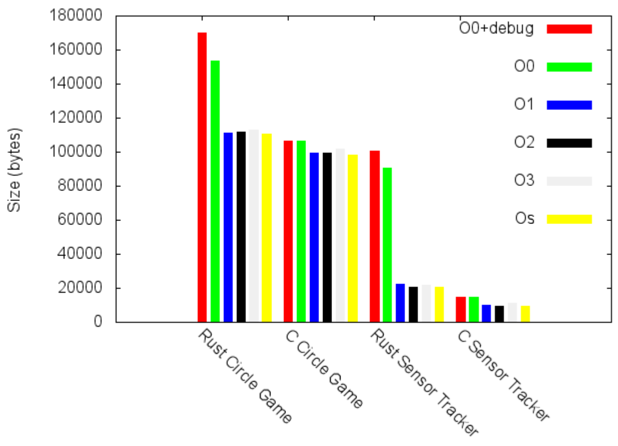


Figure 8.6: Code size for project binaries

We see here that the largest variation is between unoptimized and optimized `Rust` code. The sizes varies less for the other optimization levels. Notice that the O2 level provides a smaller binary than the O3 version, and that the Os level consistently produces the smallest binaries.

Figure 8.7 shows the code size of a minimal program to boot the `Gecko`. Both implementations contains only an infinite loop, and we evaluate these to examine the overhead of the languages.

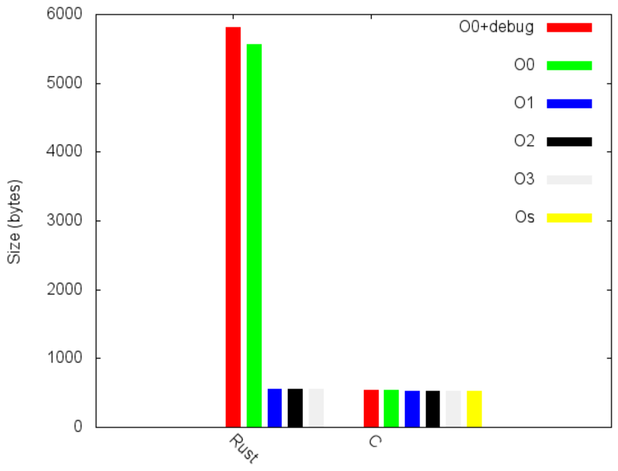


Figure 8.7: Code size for minimal program

As explained in Section 3.1, `Rust` does not require any additional initialization or setup compared to `C`. This is evident in Figure 8.7, where the binaries are the same size when optimizations have been applied. The debug and unoptimized `Rust` build is 10x larger than the optimized version.

To explain this increase in size, we look at the *zero-cost abstractions* provided by `Rust`. Some of these abstractions are built with numerous function invocations to handle complex use-patterns. To be able to debug these abstractions, it is important that the compiler keeps all these functions in the unoptimized binary. When one of these abstractions are used in the code (e.g. a `for` loop) most of these functions becomes superfluous, and be inlined after applying Dead Code Elimination (DCE).

Table 8.5 compares the size of the smallest `C` and `Rust` binaries for each of the evaluated programs. The number reported is generated by dividing the size of the `Rust` binary by the size of the `C` binary, giving the factor of which the `Rust` version is larger than the `C` version.

Program	**Relative Size**
`CircleGame`	1.22x
`SensorTracker`	2.20x
`MinimalMain`	1.00x

Table 8.5: `Rust` code size relative to `C`

We see from Table 8.5 that the `CircleGame` binary comes quite close to the `C` binaries in size. The `Rust` `MinimalMain` shows no increase over the `C` binary. In Table 8.6, we break down the size of the optimized binary of the `SensorTracker` to see which portions of the `Rust` code makes the binary size increase.

Section	**C (B)**	**Rust (B)**	**Relative**
app	1776	3964	2.23x
binding	0	184	N/A
emlib	4348	4376	1.01x
REL	0	3516	N/A
newlib	2372	792	0.33x
system	460	896	1.95x
unwind	0	3820	N/A

Table 8.6: Breakdown of binary sizes for the `SensorTracker` application

In Table 8.6, we see that there are three major non-constant contributors[1] to the increased size for the `Rust` binary:

[1]The **system** section increased with ~2x, but this section will remain constant as the complexity of the application increases.

- The application
- Rust Embedded Library
- `Rust` exception mechanism (unwind)

We see that the `newlib` implementation is reduced in the `Rust` binary. This is due to the REL library implementing some of the same functionality as `newlib`. Thus, this part of `newlib` is not included.

8.4 Heap Allocation

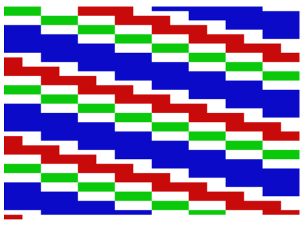
In this section we consider a small experiment to investigate possible differences in heap fragmentation caused by dynamic allocation in `C` and `Rust`. We do know, from reading the source code of the library, that the heap allocation in `Rust` builds upon the same functionality as the allocation in `C`. However, we want to verify and show this explicitly. The conducted experiment is a simple program that **1)** allocates 128 objects on the heap, **2)** replaces one object picked at random, and **3)** repeats step **2)** 1024 times. The objects are of the three sizes given in Table 8.7.

Name	**Size (32-bit words)**	**Color**
A	2	Green
B	3	Red
C	6	Blue

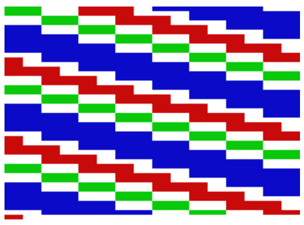
Table 8.7: Object sizes

The heap allocation pattern was recorded after the first phase of the program, and are given in Figure 8.8. The figure shows a 4KB subsection of the heap with normalized addressing to the first allocated object to aid the comparison. Each line represents 64B of memory.

We see that the initial allocation pattern is alternating between these three object sizes, and the white spaces in between are padding. These are due to alignment rules of the allocator. The objects are created in the same order in both `C` and `Rust` and we see that the allocation patterns are identical.



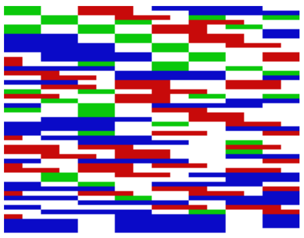
(a) C



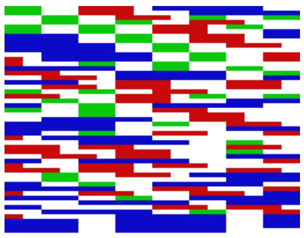
(b) Rust

Figure 8.8: Initial heap allocation of 128 objects in `Rust` and `C`

To get comparable results for both `C` and `Rust`, we make sure that the pseudo randomly picked objects are the same. This is controlled by using the same random number generator for both languages (this is the same RNG as discussed in Section 8.1). Figure 8.9 presents the heap allocation pattern after the second phase has been executed. From this figure, we see that the allocation patterns in `Rust`, on the `RustyGecko` platform, and `C`, are identical.



(a) C



(b) Rust

Figure 8.9: Heap allocation after processing in `Rust` and `C`

Chapter 9

Discussion

This project has covered a lot of implementation-level details involved with applying `Rust` to a bare-metal system, as well as presenting the ecosystem for building and distributing packages written in `Rust`. In this chapter, we look at how well the current state of `Rust` is suited for bare-metal development on embedded systems. Additionally, we revisit the language challenges that was first identified in Section 1.5 and discuss how they were solved for the `RustyGecko` platform. In Section 9.2 we discuss our investigation of the possibility of applying `Rust`'s ownership-semantics directly to hardware to avoid mutable aliasing to the peripherals. Towards the end of this chapter, we evaluate and discuss the results that were gathered as part of the `SensorTracker` and the `CircleGame` applications.

9.1 Rust for Embedded Systems

Prior to beginning this thesis, we were already aware that there were a couple of other projects that were running `Rust` bare-metal on ARM MCUs. We did not, however, know how easy it would be to get up and running with `Rust` on the EFM32. It took us less than one day to implement and execute a `Rust` blink-demo on the `STK`. The `Rust` documentation was sufficient for figuring out how to define `Rust` programs without using RSL (i.e. the ones that are annotated with `#[no_std]`), and projects like `armboot` helped us build the project for the ARM architecture. `Rust`'s runtime is comparable to `C`'s because the startup requirements in the two languages are the same, but `Rust`'s `core` library is larger and provides more functionality than the `C` standard library, which we consider to be an added bonus of `Rust`.

9.1.1 The Standard Library

`Rust` has a rich standard library that offers a strong foundation for most `Rust` programs. As we described in Section 2.1.2, the `std` crate acts like an abstraction over all the different libraries in RSL and the `rustc` compiler is itself dependent on a couple of traits to be present in this module. This crate is not applicable to all domains because it requires an OS. In our domain, we have found the dual responsibility of the `std` crate, of both providing a facade to RSL and OS-dependent functionality, to be limiting. In principle, the facade applies to our platform, but the added functionality does not. This prevents us from using the facade, and thus also all libraries that depends on `std`.

RCL does provide us with enough functionality to write idiomatic `Rust` code, but we had to implement a few workarounds in order to get support for `Rust`'s standard constructs for dynamic memory allocation. Currently, `Rust` does not have functionality to provide, or automatically compile, any of its standard libraries for target architectures other than the ones it supports by default. It was hard to handle these dependencies before we introduced the `Cargo` build process to the project. First when `Cargo` was introduced, was it easy to stay up to date with the nightly releases of the `Rust` compiler and its standard libraries.

Because our project targets an ARM processor architecture, we have to conditionally download and compile the libraries (like `alloc` and `collections`) that have functionality that we want to utilize, as described in Section 6.2. This is not necessarily a big problem in itself, as it does not complicate the process much more than the need to explicitly define the libraries as custom dependencies in the `Cargo.toml`. We do, however, think that the distinction between standard and non-standard programs make it considerably harder to enable us to use the great ecosystem that `Rust` is surrounded by.

9.1.2 Using and Distributing Libraries

We have described `Cargo` and its ability to manage package dependencies, and a package repository closely associated with `Cargo` is called `crates.io`[1]. This repository stores, at the time of writing, a couple of thousand different `Rust` crates, all made available for anyone who builds `Rust` programs with `Cargo`. The vast majority of these crates are, to the best of our knowledge, linked to `std` and utilize some part of it, either directly or transitively through a package dependency. That being said, they do not necessarily use any functionality that we have not already made available through REL in our project. This simple fact renders nearly all (if not all) packages available through `crates.io` unusable for our project, even though the functionality that many of these packages depend on might already be available through REL.

[1]`https://crates.io`

As an example to demonstrate this problem, we look to the `lazy-static`[2] project available on `crates.io`. This project allows the programmer to declare *static* variables that get initialized at *runtime*. It provides some of the same functionality that we implemented for the event-hub described in Section 7.2. We can not use this project directly because it depends on `std`. With a closer look at the project, we can see that the project author at some point did prototype an alternate (and outdated) version which was only dependent on `core`. Another example is the `smallvec`[3] project, which provides a handful of optimized versions of `Rust`'s vector structure that have a length-limit of 32 entries. Similar to the `lazy-static` project, all the dependencies for `smallvec` are included from `std`, but are also available in `core`. We have implemented a structure that is similar to `smallvec` as part of the `SensorTracker` application, but it feels like an unnecessary addition because it is already available on `crates.io` *and* it only depends on features from `core`.

This distinction between `std` and RSL feels somewhat contradictory to `Rust`'s focus on modularization and package distribution with `Cargo`. It also feels destructive for non-standard projects like ours, because we would either have to re-implement or modify the already existing projects in order to get them to work for our platform. We hope that it will get easier in time to define non-standard projects, while simultaneously being able to utilize many of the great open-source libraries that are already available.

9.1.3 Language Challenges

In Section 1.5 we identified six language challenges that must be considered when using a language in a bare-metal system. Here, we revisit each challenge and discuss how they were solved for the `RustyGecko` platform.

LC1 - Volatile read and write
`Rust` exposes two *intrinsics* for handling volatile read and write. These makes the code more verbose compared to the mechanism in `C`, where a variable is marked with the `volatile` keyword. In `Rust`, the intrinsic functions must be used each time a variable is read or written. This, however, gives the programmer more fine-grained control as a variable can be used both as volatile and non-volatile.

LC2 - Handling interrupts
Interrupt handlers, in the `RustyGecko` platform, must use the `C` ABI, because the interrupts are dispatched from the `C` runtime. This makes the code more verbose, but it is easily achievable in `Rust`. As discussed in Section 9.2, a downside to the interrupted programming model found in embedded programming for `Rust` is the reliance on global mutable state. In these circumstances, the compiler is limited in its ability to statically verify safety because accesses to these variables must be contained inside `unsafe` blocks.

[2]`https://crates.io/crates/lazy_static`
[3]`https://crates.io/crates/smallvec`

LC3 - Reading and writing hardware registers
In this thesis, we have only considered hardware devices as MMIOs. As `Rust` supports raw pointers and allows the programmer to access arbitrary memory addresses and cast these as structs, the handling of hardware registers are equally practical in `Rust` as in `C`. Given a more mature bare-metal platform in `Rust`, we foresee that even more of the compile-time ownership analysis provided by the `Rust` compiler can be used to ensure safer interactions with hardware registers.

LC4 - Static object construction
`Rust` (and `C`) have, unlike many other programming languages, no life before the `main` function. In this statement lies the fact that in the global scope, one can only initialize objects which have constant initializers. Therefore, all the initializers will only contain constant data and these can be handled by the startup mechanisms described in Section 2.6. This implies that the static object construction problem is non-existent in `Rust` programs.

LC5 - Heap allocation
Dynamic allocation in `Rust` is implemented in the `alloc` library. We were easily able to include this functionality in REL. In Section 8.4, we showed that the heap allocation in `Rust` and `C` are identical. This is due to the allocation algorithm in `Rust` being directly dependent on the `newlib` `malloc` implementation, and therefore the memory fragmentation is equal to that of the existing `C` platform. Note that this does not strictly hold true for all `Rust` platforms because they can use different allocation algorithms.

LC6 - Error handling without allocation
When the `Rust` allocator runs out of memory, it will call a function which is defined in the `alloc` library. At the time of writing, this function does not provide any error handling, as it only calls a compiler intrinsic to abort the program. This means that a `Rust` program, which runs out of memory, will not end up in an infinite error handling loop, but the program ends up with a HardFault.

9.2 Avoiding Mutable Aliases to Hardware

The problem that arises with aliasing to mutable data [6], also known as shared mutable state, are not always obvious. This is, however, often the root to problems like data races and other write-after-write issues. One of the initial problems that we wanted to investigate during this project was to see if we could apply `Rust`'s ownership-semantics directly to hardware. As described in Section 5.1, ARM MCUs, like the EFM32 that we have targeted in this project, often comes bundled with a wide range of memory-mapped hardware peripherals. Obscure problems can occur if these peripherals are accessed from *different* parts of a program *at the same time.* The section below describes a detailed example of how this can happen. Further on in this section, we look towards Rust to see if it is possible to gain assistance from some of the language features to prevent this issue statically.

9.2.1 Identifying the Problem

It is quite common to declare mutable global variables in C programs; these are accessible from every stack-frame throughout the running program. Such variables are also available in Rust, but as Section 2.1.7 describes, reading and writing to and from these variables are considered to be unsafe operations. We have also seen, in Section 5.1, that the MCUs different peripherals are memory-mapped. We can get access to a peripheral by casting a specific memory address to a program structure, which is then used as a handle to the respective peripheral.

As an example, a USART is located at memory address 0x4000C000 on the Gecko, and the bindings that we have implemented for emlib provide functions to easily initialize new handles to addresses like this. This means that every peripheral (that we have written bindings for) are accessible through common library routines. Ultimately, this also means that multiple handles to the same USART can be acquired. Note that acquiring two handles to the same peripheral will not necessarily cause any wrongdoing in a program, but problems can occur if handles to the same peripheral are acquired in different execution contexts.

This problem can be demonstrated with an example. Let us say that we have a program in which we have configured two interrupts, I1 and I2, to be triggered at differently timed intervals in the program. In the interrupt handler for I1 we initiate a data transfer of 0x1111 over the USART, and we initiate a data transfer of 0xFFFF in the interrupt handler for I2. Now, consider what happens if the I2 interrupt occurs while the interrupt handler for I1 is executing. If I2 has higher priority than I1, the execution will change scope to I2's interrupt handler, and a new USART transfer will be initiated. Effectively, a race-condition has occurred where two different execution contexts have acquired a handle to the same peripheral, and both are using this peripheral to transfer data at the same time. This might result in corrupted data to be sent over the USART, so maybe the output is something like 0x111F1FFF instead of the expected output 0x11111FFFF. Even worse, the application at the receiving end of the USART might end up with a program crash if it relies on the data to be delivered in a certain format.

9.2.2 Limitations with Our Approach

After the previous section, we are left with the following questions. Is there a way to apply Rust's ownership-semantics directly to the hardware? Moreover, is there a way for the Rust compiler to determine whether a peripheral is safe to use? As it turns out, there is no easy or straightforward way to do this, at least not by our findings.

Our approach to define a software library for the `Gecko` has been to utilize what *already* exists. We decided to write `Rust`-bindings for `emlib` because it would get the project up and running fairly quickly. This choice also meant that we were able to quickly use a wide range of peripherals and implement a couple of projects to test `Rust` in a bare-metal setting. It turns out, however, that this approach has introduced a few limitations to our system:

1) We access the peripherals through `C`-bindings, which mean that `Rust` has no control over what happens on the other side of the FFI.
2) Each peripheral structure that is used throughout the program is essentially a reference to a singleton MMIO. This means that the peripherals can be treated as *static mutable* objects, which by definition is unsafe in `Rust`.

The biggest problem with both 1) and 2) is that the bindings hide away the fact that something unsafe is happening underneath the function calls, and that some of the functions expose *internal mutable state*. An immediate proposal to fix some of the flaws in this design is:

1) Mark the `Rust`-bindings that instantiate and return a handle to a peripheral as `unsafe`.
2) Modify the bindings that write to (i.e. mutates) the peripheral control registers to require a *mutable reference* to the respective peripheral.

By implementing 1) across the `bindings` library, we will enforce the programmer to wrap every piece of code that is used to instantiate access to a peripheral with an `unsafe` block. This does not solve any problems directly, but it provokes the programmer to take extra caution when using the library, by taking on the responsibility of analyzing where there is a chance for mutable aliasing to occur. This additional caution to unsafe code has, as we described in Section 7.1, already helped us uncover a bug in `emdrv`. If we implement 2) across the library, `Rust`'s borrow-checker will be able to help us discover potential data races within a code block, but it will not be able to assist us across different execution contexts.

Another attempt would be to hide the hardware initialization process from the programmer and let it be completed automatically by the compiler, similar to what `Zinc` does, as described in Section 2.5. `Zinc` uses the Platform Tree to specify the hardware, which does the process of initializing the peripherals and saves them into a `run_args` structure that acts as their owner. This approach of initialization has two advantages:

1) Compile-time verification can guarantee that the peripherals get initialized correctly.
2) The peripherals are owned by a variable, and access to these peripherals can be controlled by `Rust`'s borrow-checker.

Point 1) is indeed a very interesting feature of `Zinc`, but it does not help us solve the problem that we are discussing in this section. Point 2) can help us ensure that all peripheral access goes through the `run_args` structure. However, this structure is only passed to the program's main loop, which has a different environment than the scopes that are defined by the interrupt handlers. However, this structure is only passed to the program's main loop, which has a different execution context than the interrupt handlers. Thus, we can defer our primary problem to be that `Rust` cannot statically reason about the peripherals' ownership because they are accessed from different execution contexts.

9.2.3 Alternative Approaches

The weaknesses that we have described throughout this section are partly introduced at the border between `Rust` and `C`. However, the main problem with data races that can occur in interrupt handlers are present in both languages. Thus, there is no obvious way that `Rust`'s ownership semantics can be used *directly* to discover and prevent data races across interrupt handlers. This is because the part of the program that is currently executing is put on hold in favor of the interrupt handler, and the new interrupt defines a different execution context. This makes it impossible to keep program state consistent between the various handlers unless it is kept in global variables.

There are, of course, other approaches to this problem other than to rely on the compiler to prevent the data races. One way to try and *prevent* this problem during or after implementation can be to *test* the program for errors that happen due to simultaneously occurring interrupts. There are several different approaches to how this can be done [15, 25], but this has not been in the scope of this thesis.

Another approach can be to treat this as a concurrency problem that we can try to solve *dynamically* instead of *statically*. We can consider the problem that we have described throughout this section to be an application-dependent issue. Because of this, we can argue that it is not the right decision to solve this issue as part a low-level library like `emlib` and its bindings. Instead, we can define an auxiliary library that can solve this problem with an opinionated approach, which might apply to a lot of different applications, but not to all.

In Section 7.2, we described the implementation of a library that takes on the task of hiding the various interrupt handlers and instead expose interrupts through *closures* that can be registered at runtime. It is possible to extend this library to make it *safe* to dispatch new interrupts at runtime. E.g. by identifying the different possibilities of states the program can be in at the time of an interrupt, as well as the various actions that can be done depending on this state. The library can then provide routines to either *lock* the access to a peripheral during an interrupt or provide *channels* that can be used to communicate directly with the peripheral in a safe manner. Note that this is not an issue that can only be solved with `Rust`, it can be implemented in any language, but `Rust` might prove to be exceptionally well-suited for the task. As we described in Section 2.1.6, `Rust` was specifically developed to be a good foundation for modern applications that require concurrency. Additionally, it becomes evident that `Rust`'s notion of ownership was the key to make it both safe and efficient to implement different concurrency-paradigms. Unfortunately, due to time restrictions, we could not look into the details of how this library can be expanded to handle this problem. Instead, we propose it as part of the future work, described in Section 10.3.

9.3 Project Evaluations

This section discusses the results that were gathered as part of the `SensorTracker` and `CircleGame` projects and presented in Chapter 8. First, we will look at the choice of projects and method of evaluation. Then, we will discuss each of the separated metrics performance, energy efficiency, and code size in isolation, before we wrap up this section by discussing the current state of `Rust` programming on a bare-metal system in light of our results.

9.3.1 Projects and methods

For the platform evaluation of this project, we chose to develop two main example applications, one to evaluate performance and one for energy efficiency. These two *qualitative* studies were chosen in order to focus on evolving the platform guided by these metrics. The reason for not choosing a more *quantitative* study with a larger number of applications was due to the focus on platform development and because there was benchmark suite written for `Rust` that existed for bare-metal systems. The quantitative approach would produce a larger set of results, which would provide a better foundation to evaluate the platform. Our focus here was to create the platform and to include some preliminary evaluations to validate the feasibility for further development and evaluation.

For this purpose, the qualitative project approach provided us with a few driving metrics and feature sets to motivate the development. At the same time, we kept the total code base small enough to facilitate rapid changes in case a better better approach was discovered, like the build system described in Chapter 6.

A third option could have been to develop a suite of micro benchmarks. This option was not chosen since we wanted to create *larger* projects to stress the programmability and code organization of the platform.

9.3.2 Performance

In Section 8.1, we looked at the performance of the graphical game application, `CircleGame`. It is evident, from our results, that the performance of the `Rust` version is comparable and even greater than that of equivalent `C` code. Although a graphical game application and the FPS performance metric is not typical for the embedded processors targeted here, this qualitative result suggests that the abstractions provided by the `Rust` language are *zero cost* when considering performance.

9.3.3 Energy

We must emphasize that energy consumption measurements presented in Section 8.2 are preliminary, and that the focus for the `SensorTracker` application was primarily used to provide an application in this domain. The main problem with reading too much into these results is that the `Rust` and `C` implementations share a substantial amount of the library code, which is written in `C`. The application code here is just a thin wrapper around the libraries. When we dug deeper into the analysis of the application, we found that most of the time, the application spends its time in a busy-wait state, waiting for sensor data to become available. In these circumstances, the difference between the two languages are not evident.

From the results, we can deduce that the variance in the energy consumption in the tested applications are larger within the different levels of optimization in the `C` compiler, compared to the introduction of the `Rust` application layer. As we saw in Section 8.2 the variance is more correlated to the cache hit ratio than the programming language we are using. At least this result points in the direction of the two language being equal in this domain.

In order to evaluate the `Rust` language thoroughly in this domain, a larger portion of the code that constitutes the library must be written in `Rust`. In addition, a more suitable example must be employed, where the actual code is the dominant factor and not the busy-waits.

9.3.4 Code Size

From our code size analysis, we have made three discoveries which are important to discuss. This discussion should be read in light of the fact that the `Rust` compiler is a newly released compiler and is being compared to a `C` compiler, which has been used in production for years.

Large unoptimized Rust build

As seen throughout all of our measurements in `Rust`, the unoptimized binaries are significantly larger than the optimized binaries. The cause for this seems to be that the many abstractions of the `Rust` language are implemented by adding levels of indirection through function calls. The `for` loop described in Section 2.1.2 is an example of this. These *extra* functions, which are eliminated when optimized, make the compiler produce substantially larger binaries without the optimizations. This shows that the *zero-cost abstractions* of `Rust` are not *zero-cost* when analyzed from this angle.

Rust code can be significantly larger than C equivalents

The optimized `SensorTracker` application written in `Rust` proved to be several times the size of the `C` version. This was further analyzed to reveal that the increase in size is due to three factors, reiterated here:

- The application code itself
- The `Rust` Library
- `Rust` exception mechanism (unwind)

There is a proposal make the exception mechanism optional with a compiler flag, this would provide a substantial reduction in code size. Even though it might be useful to keep the mechanism in a production environment, this reduction can be helpful to reduce the size of the debug binaries.

There is zero size overhead of using optimized `Rust`

The Minimal Main application shows that using `Rust` by itself does not incur an increase in size. It is the size of the software libraries, in our results, that increases the size of the `Rust` binaries.

9.3.5 Rust in Embedded Systems

The results discussed here are positive for further exploration of `Rust` in the embedded domain. One critical task in an embedded system is to meet a strict deadline imposed by timely interrupts. Both the `SensorTracker` and `CircleGame` expose similar performance for both language implementations,which provides an important result.

On the other hand, when we look at code size, we see a larger challenge for the `Rust` language. The focus on *Zero-cost Abstractions* does not seem to take into account the size of the end binary, especially in the builds where optimizations are not applied. This does not cause any problems in a system where storage for code and data is plenty, but this is not the case in an embedded system. By comparing the smallest processors of the EFM32 Product Family given in Section 2.3.1 and the size of the debug builds presented in Section 8.3, we see that a debug build of the Minimal Main example will not fit in the smallest models. The inability to debug an application on the actual target hardware can be a significant problem in not only development and testing stages, but also for tracing bugs in production systems.

Chapter 10

Conclusion

In this chapter, we draw conclusions derived from the discussion of the `RustyGecko` platform. We also look back at the requirements that were defined in Chapter 1, and give an evaluation of the project's success. Finally, we give our thoughts on further developments to improve the `RustyGecko` platform, and suggest some changes that could make `Rust` more suited for bare-metal systems.

10.1 The RustyGecko Platform

In this thesis, we have presented the `RustyGecko` platform for programming a bare-metal system by using the `Rust` programming language. This platform consists of a subset of the `Rust` standard library and a handful of libraries that define bindings for the EFM32 peripheral API. In total, we have been able to utilize many great aspects that surround the `Rust` programming language in the `RustyGecko` platform.

One of the tools we were able to incorporate is the `Cargo` package manager. This enabled us to give the `RustyGecko` platform a modular design, which makes the different parts of the platform reusable as isolated units of code. However, the RSL is an implied dependency for all standard `Rust` projects. Because of this, and given the current design of RSL, it is hard for non-standard projects to utilize third-party libraries.

`Rust` implements many interesting features, among these are its ability to statically prevent data-races. We attempted to apply these concepts directly to the hardware peripherals but found the resulting programming model to be too limited. Instead, we propose to explore this idea further by considering a more dynamic approach for future work.

From our measured results, we showed that on the `RustyGecko` platform, we can still make applications that perform as well as the existing `C` platform. This conclusion is derived from our qualitative study of performance and energy consumption for the two applications that was developed on this platform. However, we did find indications that the platform produces larger binaries, which make `Rust` applications more expensive in terms of hardware costs. The binaries are stored in flash memory and the size of this memory correlates with the cost of the microcontroller. The increased cost in hardware can be expensive for resource constrained applications, which are shipped in the millions. This, consequently, can turn out to be a hindrance for applications in the industry.

10.2 Requirements

In Chapter 1, we presented three requirements as interpreted from the Project Description for this thesis. In this section, we describe how each of these requirements were fulfilled.

R1 - Identify and describe the requirements for a bare-metal platform in `Rust`
We identified six language challenges that was important to solve to get `Rust` to work on a bare-metal system. These challenges were all handled in the implementation of the `RustyGecko` platform.

R2 - Prototype a bare-metal software platform for `Rust` on the EFM32
We consider the `RustyGecko` platform to fulfill this requirement. The prototype provides the same functionality as the existing `C` platform in principal, and needs only be fleshed out to have full support.

R3 - Evaluate code size, performance and energy consumption
Throughout Chapter 8, we presented our results of measuring the `RustyGecko` platform, and our evaluation of the measurements are given in Chapter 9 to satisfy this requirement.

Based on these requirements and their solutions, we consider the project as a whole to solve the problems deduced from the Project Description. This conclusion leads us to further conclude that the project was successful.

10.3 Future Work

We have worked on many different projects on the `RustyGecko` platform throughout this thesis. In this section, we suggest some of these projects as future work. We also suggest some new project ideas based on our experiences during the development of the `RustyGecko` platform.

Bindings
As we presented in Section 5.2, the `RustyGecko` platform consists of partially

finished bindings. An obvious extension to our project is to continue and finalize the binding libraries for the `emlib`, `emdrv` and CMSIS libraries. The foundations for these bindings have been laid out, so the implementations here are not challenging, only time-consuming. An alternative approach is to use a bindings generator, such as `bindgen`[1], to generate the bindings automatically. Note that the binding effort might be redundant altogether, as the `Rust` roadmap states that the project wants to develop better integration with `C` and `C++` code [4]. This might eventually lead to bindings like these being made obsolete and that `C` libraries can be called into based on their header files alone.

Trait-based Peripheral Access
An aspect that we did not go into in this project is `Rust`'s ability to, by using traits, redefine the semantics when using values. This concept can possibly be applied to remove the verbosity of the volatile loads and store of peripheral control register operations, as discussed in Section 9.1.3.

The Standard Library
As discussed in Section 9.1, we found the current basis for writing reusable libraries to be limiting for our platform. One of the major problems is the interoperability between standard and non-standard libraries, which limits the amount of third-party libraries that can be utilized for the `RustyGecko` platform. We leave it as future work to go into detail on ways to solve this problem, by either applying a different approach or to modify the blocking obstacle in the `std` crate.

Rust Embedded Library
In Section 7.3, we looked at a library that provided higher-level abstractions by using the language features of `Rust`. This library can be further developed to include better initialization procedures for the peripherals, as in `Zinc`, and extended to provide abstractions for more peripherals.

Safe Access to Hardware
The interrupt-driven programming model that is used to programming of embedded systems did not prove to be as applicable to `Rust` and its ownership-semantics as we had hoped. `Rust`'s ownership system helps to rule out data races in programs [7]. We believe that the ownership system can be utilized in a new framework, based on the one that was described in Section 7.2 and further discussed in Section 9.2, for initializing and dispatching interrupts. It will be interesting to see if `Rust`'s ownership-semantics can help to apply a more dynamic approach to this framework, in order to ensure safe access to hardware peripherals.

Using Rust at the Library Layer
Throughout this thesis, we have only worked with the `Rust` language at the application layer language and binding to `C` for library support. It can be interesting to do this the other way around. Concretely, parts of the `emlib`

[1]`https://crates.io/crates/bindgen`

library can be replaced with a `Rust` implementation and still expose the same API to the user and be callable from a `C` application.

Rust-only Solution

We chose to base the `RustyGecko` platform on the software libraries that were already available for the `Gecko`. This enabled us to quickly shape the platform and explore many different project ideas. However, we argued in Section 9.3 that to make a more thoroughly comparison of the `C` and `Rust` languages in this domain, more of the platform have to be implemented in `Rust`. A new direction for the platform can be to adapt the `Zinc` project for the `Gecko`, and to port the actual implementations of the `emlib` library to `Rust`. This approach can provide a better basis for an evaluation of `Rust`. It is also possible that `Rust`'s `unsafe`-semantics can help to uncover more bugs in the `C`-implementation of `emlib`.

Bibliography

[1] Fearless Concurrency with Rust. Available: blog.rust-lang.org/2015/04/10/Fearless-Concurrency.html. [Accessed: 2015-05-05].

[2] Gartner. Available: http://www.gartner.com/newsroom/id/2905717. [Accessed: 2015-06-09].

[3] GCC ARM Embedded. Available: https://launchpad.net/gcc-arm-embedded. [Accessed: 2015-06-09].

[4] Priorities After 1.0. Available: https://internals.rust-lang.org/t/priorities-after-1-0/1901. [Accessed: 2015-06-10].

[5] Rust Once, Run Everywhere. Available: http://blog.rust-lang.org/2015/04/24/Rust-Once-Run-Everywhere.html. [Accessed: 2015-04-27].

[6] The Problem With Single-threaded Shared Mutability. Available: http://manishearth.github.io/blog/2015/05/17/the-problem-with-shared-mutability/. [Accessed: 2015-06-02].

[7] The Rust Programming Language. Available: http://doc.rust-lang.org/book. [Accessed: 2015-05-26].

[8] The Rust Project FAQ. Available: https://doc.rust-lang.org/complement-project-faq.html. [Accessed: 2015-04-27].

[9] Using the GNU Compiler Collection (GCC). Available: https://gcc.gnu.org/onlinedocs/. [Accessed: 2015-06-11].

[10] VDC Research. Available: http://www.oracle.com/us/technologies/java/java-embedded-market-wp-2179018.pdf. [Accessed: 2015-06-09].

[11] zinc.rs. Available: http://zinc.rs/. [Accessed: 2015-06-09].

[12] Dinakar Dhurjati, Sumant Kowshik, Vikram Adve, and Chris Lattner. Memory safety without garbage collection for embedded applications. *ACM Transactions on Embedded Computing Systems*, 4(1):73–111, 2005.

[13] Jan Vitek Filip Pizlo, Lukasz Ziarek. Real Time Java on resource-constrained platforms with Fiji VM. 2009.

[14] Dan Grossman, Greg Morrisett, Trevor Jim, Michael Hicks, Yanling Wang, and James Cheney. Region-based memory management in cyclone. *ACM SIGPLAN Notices*, 37:282, 2002.

[15] Makoto Higashi, Tetsuo Yamamoto, Yasuhiro Hayase, Takashi Ishio, and Katsuro Inoue. An effective method to control interrupt handler for data race detection. *Proceedings of the 5th Workshop on Automation of Software Test - AST '10*, pages 79–86, 2010.

[16] Silicon Labs. DIRECT MEMORY ACCESS - Application Note. pages 1–7, 2004.

[17] Silicon Labs. User manual - Development Kit EFM32GG-DK3750. 2013.

[18] Silicon Labs. User manual - Starter Kit EFM32GG-STK3700. 2013.

[19] Silicon Labs. Biometric EXP Evaluation Board User's Guide. 2014.

[20] Silicon Labs. EFM32GG Reference Manual. 2014.

[21] Silicon Labs. Mixed-Signal 32-bit Microcontrollers. 2014.

[22] Silicon Labs. TIMER - Application Note. 2014.

[23] Alessandro Orso and Gregg Rothermel. Software Testing: A Research Travelogue (2000–2014). pages 117–132, 2014.

[24] Alexandre Petit-Bianco. No Silver Bullet - Garbage Collection for Java in Embedded Systems.

[25] John Regehr. Random testing of interrupt-driven software. *Proceedings of the 5th ACM international conference on Embedded software*, pages 290–298, 2005.

[26] Nikhil Swamy, Michael Hicks, Greg Morrisett, Dan Grossman, and Trevor Jim. Safe manual memory management in Cyclone. *Science of Computer Programming*, 62(2):122–144, 2006.

[27] Ca Valhouli. The Internet of things: Networked objects and smart devices. *The Hammersmith Group research report*, (february):1–7, 2010.

[28] Paul R. Wilson. Uniprocessor garbage collection techniques. *Memory Management*, (September):1–42, 1992.