

Foundations for Constrained Debugging Techniques

*Finding software faults in constrained environments with sound out-of-place
and multiverse debugging techniques*

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for my darling cabbage

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Declaration

This dissertation was written in the period from 2021 to 2025, and the works therein have been published or submitted for publication at peer-reviewed conferences and journals, and have been represented at various conferences and workshops.

Published works

The following previously published work feature prominently within this dissertation. They are integrated in, respectively, Chapter 3, Chapter 4, Chapter 5, and Chapter 6.

Tom Lauwaerts, Robbert Gurdeep Singh, Christophe Scholliers. *WAR-Duino: An embedded WebAssembly virtual machine*. In Journal of Computer Languages, Volume 79. Elsevier, 2024.

Tom Lauwaerts, Carlos Rojas Castillo, Robbert Gurdeep Singh, Matteo Marra, Christophe Scholliers, and Elisa Gonzalez Boix. *Event-Based Out-of-Place Debugging*. In MPLR, pages 85–97. ACM, 2022.

Tom Lauwaerts, Maarten Steevens, Christophe Scholliers. *MIO: Multi-verse Debugging in the face of Input/Output*. In OOPSLA. ACM, 2025.

Tom Lauwaerts, Stefan Marr, Christophe Scholliers. *Latch: Enabling large-scale automated testing on constrained systems*. In Science of Computer Programming, Volume 238. Elsevier, 2024.

Preparing for submission

At the time of writing, the following prominently featured works were submitted at peer reviewed conferences or journals, and are still under review or being prepared for resubmission.

Tom Lauwaerts, Maarten Steevens, Christophe Scholliers. *Stateful Out-of-place Debugging*. (Recommended for resubmission by ECOOP'25)

Demonstrations and other presentations

We list here the more formal presentations, and demonstrations not listed before. We have left out poster presentations and talks outside of international conferences.

Tom Lauwaerts, Robbert Gurdeep Singh, Christophe Scholliers. *Light-weight IOT abstractions for Embedded WebAssembly*. Presented at VMIL'21.

Tom Lauwaerts, Carlos Rojas Castillo, Elisa Gonzalez Boix, Christophe Scholliers. *Demo: Debugging Constraint Devices with EDWARD*. In Mo- biSys'23, pages 602-603. ACM, 2023.

Tom Lauwaerts, Carlos Rojas Castillo, Elisa Gonzalez Boix, and Christophe Scholliers. *Out-of-Place Debugging on Constraint Devices with the EDWARD Debugger (Demo)*. In DEBT'23, pages 3-4. ACM, 2023.

Tom Lauwaerts. *Out-of-place Multiverse Debugging for Constraint Device*. At the ACM Student Research Competition (SRC) at ECOOP/ISSTA. 3rd place. ACM, 2023.

Remainder

Other publications that are not directly part of this dissertation:

Maarten Steevens, **Tom Lauwaerts**, Christophe Scholliers. *Remote Con- colic Multiverse Debugging*. (Preparing for resubmission)

Maarten Steevens, **Tom Lauwaerts**, Francisco Ferreira Ruiz, Christophe Scholliers. *WARDuino on Open Bot Brain: Building and programming Lego robots in high-level languages using WebAssembly* (Preparing for submis- sion)

Software artifacts

The software developed as part of this dissertation is available publicly on the Theory and Operations of Programming Languages Lab's [GitHub page](#). The following software was developed as part of this dissertation:

WARDuino virtual machine and debuggers. [TOPLLab/WARDuino](#)

WARDuino VSCode plugin. [TOPLLab/WARDuino-VSCode](#)

The MIO frontend. [TOPLLab/MIO](#)

The Latch testing framework. [TOPLLab/latch](#)

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Permit me to
paraphrase.

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Tom Lauwaerts
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Vulgariserende samenvatting

Programma's schrijven is moeilijk, en ontwikkelaars maken onvermijdelijk fouten, die we in de informatica bugs noemen. Het opsporen van deze bugs, debugging, neemt een groot deel van de ontwikkelaar's tijd in beslag. Helaas zijn de hulpmiddelen die hen hierbij zouden moeten helpen, zogenaamde debuggers, in de praktijk vaak nogal verouderd. Dit geldt vooral voor *microcontrollers*, ofwel embedded apparaten—heel kleine computers, die noodzakelijk beperkt zijn in hun capaciteit, maar daarom vaak worden gebruikt in internet-of-things toepassingen, zoals je slimme thermostaat, fitness tracker, WiFi-lampen, enzovoort.

Er is een duidelijke behoefte aan betere debugging-tools bij de ontwikkeling van embedded software. Echter, de aard van deze apparaten brengt verschillende obstakels met zich mee die de ontwikkeling van geavanceerdere debugging-technieken bemoeilijken. Deze obstakels kunnen worden onderverdeeld in zeven hoofduitdagingen.

- C1** Er is geen formeel raamwerk waarin debuggers beschreven en ontwikkeld kunnen worden, en geen formele definitie van hun correctheid.
- C2** Het is moeilijk om programma's op microcontrollers te instrumenteren doordat ze gecompileerde talen gebruiken en *bare-metal* uitvoeringsomgevingen.
- C3** Ontwikkeling van embedded software wordt gekenmerkt door een trage ontwikkelcyclus onder andere door eenvoudige programmeertalen, lage interoperabiliteit tussen hardwareplatformen, trage upload, hardware-limitaties, en weinig opties voor debuggers.
- C4** De hardwarebeperkingen van embedded apparaten maken het moeilijk om debuggers naast de software uit te voeren, voornamelijk de gelimiteerde rekenkracht en geheugen.
- C5** Typische interrupt-gedreven programma's versturen het debugproces.
- C6** Huidige embedded debuggers zijn niet uitgerust om niet-deterministische bugs te debuggen.
- C7** Hoe kunnen we *multiverse debugging* toepassen op een concrete uitvoering van een programma met veel I/O interacties.

Op dit moment gebruiken ontwikkelaars van microcontrollers twee inefficiënte debugging-technieken, die niet voldoende zijn om deze uitdagingen te overkomen.

“Verouderd” is hier het juiste woord, aangezien breakpoints al in de jaren zestig zijn uitgevonden.

Ten eerste gebruiken ontwikkelaars *print statement debugging*, waarbij ze print statements toevoegen aan hun code om informatie op bepaalde punten in het programma af te drukken. Op deze manier proberen ze na afloop informatie over de uitvoering van het programma af te leiden. Dit leidt tot een trage, iteratieve cyclus van print statements toevoegen en verwijderen, opnieuw compileren, opnieuw uploaden en opnieuw uitvoeren van de software.

Ten tweede kunnen ontwikkelaars proberen een hardware-debugger op te zetten, een extra stuk hardware dat verbinding maakt met de microcontroller —en zo inspectie van de program mastatus mogelijk maakt. Deze hardware-debuggers zijn echter vaak duur en lastig op te zetten. Bovendien ondersteunen de bijbehorende software tools, met name *remote debuggers*, alleen de meest eenvoudige, en standaard debugbewerkingen.

In dit proefschrift stellen we verschillende nieuwe debugging-technieken voor die specifiek zijn ontworpen om deze uitdagingen te overwinnen, en hopelijk de weg vrijmaken voor een nog bredere variëteit aan geavanceerde en betere debugging-technieken.

Onze eerste bijdrage is een nieuwe manier van remote debugging voor embedded apparaten, gebaseerd op een virtuele machine in plaats van op hardware-debuggers. We hebben een op WebAssembly gebaseerde virtuele machine ontwikkeld, genaamd WARDuino, die op de microcontroller draait. Dit stelt ontwikkelaars in staat om hun apparaten te programmeren in abstractere programmeertalen zoals JavaScript, Python en Rust, en om een remote debugger te gebruiken zonder dat er hardware-debuggers nodig zijn.

Onze tweede bijdrage bouwt voort op de eerste, door een nieuwe debugging-techniek toe te voegen, die we *stateful out-of-place debugging* noemen. Deze techniek verplaatst het grootste deel van de debug-sessie van de microcontroller (server) naar de computer van de ontwikkelaar (client), waar men kan profiteren van de volledige rekenkracht van moderne computers. Hierdoor kunnen debuggers de beperkingen van de microcontroller omzeilen en makkelijker geavanceerde debugging-technieken ondersteunen. Tegelijkertijd behoudt de techniek toegang tot de hardware-specifieke functies van de microcontroller, waardoor er nog steeds de illusie is van remote debugging.

De stateful out-of-place debugger pakt ook de derde uitdaging aan, door alle asynchrone gebeurtenissen, zoals hardware-interrupts, vast te leggen en door te sturen naar de client. Daar onderbreken deze gebeurtenissen de uitvoering van het programma niet automatisch; in plaats daarvan kan de ontwikkelaar via de debugger zelf kiezen op welk moment een gebeurtenis wordt geactiveerd. Dit voorkomt de verwarring die kan ontstaan wanneer een debug-sessie plotseling wordt onderbroken door hardware-interrupts, en geeft

ontwikkelaars meer middelen om specifieke *interleavings* van gebeurtenissen of andere voorwaarden die tot bugs leiden, te recreëren.

De vierde uitdaging wordt aangepakt door onze laatste debugger, genaamd MIO: een *multiverse debugger* voor input- en outputprogramma's op microcontrollers. Multiverse debugging maakt het eenvoudiger om niet-deterministische programma's te debuggen, door ontwikkelaars de mogelijkheid te geven om alle mogelijke uitvoeringspaden te verkennen. Helaas kan het debuggen van programma's met input/output-operaties via bestaande multiverse debuggers leiden tot het verkennen van ontoegankelijke programmataten—staten die tijdens normale uitvoering niet voorkomen. Dit kan het debugproces ernstig belemmeren, omdat de programmeur veel tijd kan besteden aan het onderzoeken van dergelijke staten, of erger nog, ten onrechte kan aannemen dat er een bug in de code zit, terwijl het probleem in werkelijkheid door de debugger zelf wordt veroorzaakt. Om dit op te lossen, introduceert MIO een nieuwe benadering van multiverse debugging, die een breed scala aan input/output-operaties kan ondersteunen—en deze zo nodig kan omkeren tijdens het verkennen van het “*multiverse*” aan uitvoeringspaden.

Onze vierde bijdrage is een nieuw testframework, genaamd Latch, voor het testen van embedded apparaten, en in het bijzonder de in dit proefschrift ontwikkelde debuggers. Ten eerste implementeert het framework een nieuwe testmethode, die we *managed testing* noemen, waarbij een debugger wordt gebruikt om geautomatiseerde tests op de microcontroller uit te voeren—gelijkaardig aan de handmatige testscenario's die ontwikkelaars normaal zelf op de hardware uitvoeren. Ten tweede gebruikt Latch hetzelfde principe als stateful out-of-place debugging om grote test suites op microcontrollers uit te voeren.

Lay summary

“Antiquated” is the right word as breakpoints were invented in the sixties.

Writing programs is hard, and developers are bound to make mistakes, which we call *bugs* in computer science. The work of finding these bugs, takes up a lot of a developer’s time. Unfortunately, the tools that should help them with this task, debuggers, are often quite antiquated in practice. This is especially true for *constrained devices*, or embedded devices, which are small computers that are often used for internet of things applications, such as your smart thermostat, fitness tracker, Wi-Fi lights, and so on.

There is a clear need for better debugging tools in embedded software development. However, the nature of the targeted devices poses several tough hurdles that stand in the way of more advanced debugging techniques. These obstacles can be split into seven main challenges.

- C1** There are *no formal foundations* for how to develop good debuggers on constrained or unconstrained devices; neither how to describe their operations or what correctness could mean for these operations.
- C2** Current embedded software development uses low-level compiled programming languages and bare-metal execution environments that make it difficult to instrument the software running on the constrained devices.
- C3** Current embedded software development is characterized by a cumbersome development experience due to low-level coding, lack of portability across platforms, slow deployment, hardware limitations, and limited debugger options.
- C4** The *memory limitations* of embedded devices make it difficult to run debuggers alongside the target software, and the *processing constraints* prevent the adoption of more advanced debugging techniques.
- C5** Typical *interrupt-driven programs* interfere with live debugging processes by arbitrarily changing the execution flow of a program.
- C6** Current embedded debuggers are not equipped to *debug non-deterministic bugs* caused by their I/O intensive nature.
- C7** How can multiverse debugging be applied to concrete executions and enable live exploration of the multiverse in the presence of I/O?

Currently, developers of embedded devices use two inefficient debugging techniques, which are not well equipped to handle the challenges of debugging constrained devices.

First, developers use *print statement debugging*, where they insert print statements in their code to print out information at certain points in the program. This way they can try and infer information about the program’s execution after it has run. This leads to a slow iterative process of adding and removing print statements, recompiling, re-uploading, and rerunning the software.

Second, developers can try and setup a hardware debugger, which is an additional piece of hardware that connects to the embedded device—enabling the inspection of the program state. However, these hardware debuggers are often expensive, and difficult to set up. Moreover, the software tools, specifically *remote debuggers*, that use them only support the most basic debug operations.

In this dissertation, we propose several new debugging techniques that are specifically designed to overcome these challenges, and hopefully pave the way to an even wider variety of advanced, and better debugging techniques.

Our first contribution, is a new virtual machine-based approach to remote debugging embedded devices, rather than hardware-based. We developed a WebAssembly-based virtual machine, called WARDuino, that runs on the embedded device. It allows developers to program their devices in high-level languages, such as JavaScript, Python, and Rust, and to use a remote debugger without the need for hardware debuggers.

Our second contribution, builds on top of the first, by adding a new debugging technique called *stateful out-of-place debugging*. The technique moves most of the debugging session from the embedded device (*server*) to the developer’s computer (*client*), where they can use the full range of compute power available to modern computers. This allows debuggers to evade the constraints of the embedded device, and to use advanced debugging techniques. However, the technique still maintains access to the hardware-specific features of the embedded device, providing the illusion of remote debugging.

The stateful out-of-place debugger also addresses the fourth and fifth challenge, by capturing all asynchronous events, such as hardware interrupts, and forwarding them to the client. Here, the events do not automatically interrupt the program’s execution, instead the developer can use the debugger to trigger events at a moment of their choice. This prevents the confusion that can arise when the debugging session is interrupted and diverted by hardware interrupts, and gives developers more tools for recreating specific interleavings of event or other conditions that give rise to the bugs they are hunting.

The sixth and seventh challenge are addressed by our third contribution, and final debugger called *MIO*, a multiverse debugger for input and output pro-

grams on constrained devices. Multiverse debugging makes it easier to debug non-deterministic programs by allowing developers to explore all potential execution paths. Unfortunately, debugging programs that involve input/output operations using existing multiverse debuggers can reveal inaccessible program states, i.e., states which are not encountered during regular execution. This can significantly hinder the debugging process, as the programmer may spend substantial time exploring and examining inaccessible program states, or worse, may mistakenly assume a bug is present in the code, when in fact, the issue is caused by the debugger. To solve this, MIO presents a novel approach to multiverse debugging, which can accommodate a broad spectrum of input/output operations—and reverse them as necessary while exploring the multiverse of execution paths.

Our fourth contribution is a new testing framework called *Latch*, for testing embedded devices, and in particular the debuggers developed in this dissertation. First, the framework implements a novel test approach, we call *managed testing*, which uses a debugger to run automated test scenarios on the embedded device—similar to manual test scenarios that developers would typically run on the hardware themselves. Second, *Latch* uses the same principle behind *stateful out-of-place debugging* to run large test suites on embedded devices.

*I don't know if you have had the same experience,
but the snag I always come up against when I'm telling a story
is this dashed difficult problem of where to begin it.*

Bertie Wooster, *Right Ho, Jeeves*

Chapter 1

Introduction

*If debugging is the process of removing software bugs,
then programming must be the process of putting them in.*
— Edsger W. Dijkstra

As long as people write programs for computers so will software continue to have bugs and mistakes. That is not pessimism; it is reality. After all we live in an imperfect world. No formal method, nor model checker, or type system can ever eliminate all mistakes—especially, for software which interacts with this imperfect, and unpredictable world. This is where debuggers—inevitably—come in.

1.1 The nature of programming mistakes

Programming mistakes come in many forms, and have many causes (McCauley et al., 2008). Some are simple syntax errors or off-by-one mistakes that static or model checkers can easily catch (García-Ferreira et al., 2014). Others have deep, and complex causes such as timing issues in concurrent systems (Li et al., 2023, Lu et al., 2008), memory corruption from hardware quirks (Bojanova and Eduardo Galhardo, 2021, Dessouky et al., 2018, Schroeder et al., 2009), non-deterministic edge cases triggered only under rare input conditions (Weiss et al., 2021), and so forth (Catolino et al., 2019). Crucially, many real-world bugs are not predictable or even known in advance (Mogul, 2006, Ubayashi et al., 2019).

This is why automated verification (D'Silva et al., 2008, Rodriguez et al., 2019), however powerful, has limits. Formal proofs and model checking work only when the system and its requirements can be fully specified and the relevant properties articulated. But many software systems today are too large, too dependent on external environments, or too hastily evolving for perfect formalization. No model or simulation can capture every single aspect of the real world (Khan et al., 2011, Roska, 1990) and so cannot detect every possible bug. In these cases the only path forward is empirical investigation.

This kind of empirical investigation is what we call “*debugging*”, and was best described by Andreas Zeller in his definitive guide, “*Why Programs Fail*:

A Guide to Systematic Debugging" (Zeller, 2005), which provides a thorough overview of debugging as a part of software development. The book describes a scientific approach to isolating bugs, and discusses best practices, common tools, and novel techniques.

1.2 What are debuggers?

The term debuggers is a rather ambiguous term, and can refer to any tool that helps with the task of debugging. However, there are many such tools—not just your typical online debugger with breakpoints and steps found in today's standard development environments. Instead, this goes from popular remote debuggers such as GDB, to automatic debuggers, or from advanced visualizers for reactive programs, to omniscient debuggers that can go forwards and backwards in time—debuggers really do come in all shapes and sizes.

This diffuseness suggests that we may never arrive at a more detailed, and universally accepted definition for debuggers—other than any tool that helps with debugging. We can, however, define the type of debuggers we consider in this dissertation more concretely. The scope of this work is limited to what we call *manual debuggers*.

Definition 1-1. (Manual debugger) A debugger is a tool that enables developers to deterministically observe a program's execution, monitor its state, and control the flow of execution.

By this definition, we exclude automatic debugging, but include a whole range of manual debugging tools, from offline to online debuggers, from remote to local debuggers, from omniscient to reversible debuggers, and so forth. To give the reader more context, we will briefly discuss the history of debuggers, their evolution, and highlight some of the different classes of debuggers that have been developed over the years.

1.3 The history of debuggers

Actually, the term *bug* was already used to refer to a fault in a machine in the late nineteenth century (Wills, 2022).

Debugging has been central to programming since the earliest days of computer science. The term itself is often traced to *Grace Hopper's famous 'bug'* story from 1947, when a literal moth was found shorting a relay in the Harvard Mark II computer (Cohen, 1994).

No history of debugging is complete without also mentioning Maurice Wilkes' famous anecdote, describing the first time he experienced the need for debugging back in 1949: "*As soon as we started programming, [...] we found*

to our surprise that it wasn't as easy to get programs right as we had thought it would be. [...] Debugging had to be discovered. I can remember the exact instant [...] when I realized that a large part of my life from then on was going to be spent in finding mistakes in my own programs." (Spinellis, 2018, Wilkes, 1979) The term *debugging* came into circulation shortly after Wilkes' famous encounter. From that point on, debuggers evolved alongside programming languages and computer systems, from the early days of assembly language and punch cards to the high-level languages we use today. Wilkes' description still sums up the need for debugging perfectly today.

1.3.1 Debuggers in all shapes and sizes

During the early days of computer programming in the 1950s, most debugging was necessarily done with print statements, added to the punch cards used in those days (Backus et al., 1957). One of the first improvements on this system, was to add new macros specific for debugging, which help improve traces of the program, such as those added in the *share* operating system for the IBM 709 (Hanford, 1960). These kind of macros can be considered the first iterations of so called *offline debuggers*, which are debuggers used to analyze a program after it terminated, usually through traces of the program's execution. Early on they were often called *post-mortem debuggers* (Green, 1960), however, today post-mortem refers to a specific type of offline debugger, which analyzes the program after it has crashed (Pacheco, 2011).

During the same decade, the first *online debuggers* were developed as well, which in contrast enable interactive inspection, control, and modification of a program's execution state while the program is running. One of the earliest examples is the RCA 501 system (Smith and Hurewitz, 1958), which included six breakpoint switches, and a paper tape reader and monitor printer for debugging. Of course computers have changed dramatically since the 1950s, and the days of magnetic tapes are long gone. Still, the debugging tools of the RCA 501 system are very similar to the core debug operations present in most modern debuggers today. A clear illustration of how slow adoption of new debugging techniques has been in some regards (Perscheid et al., 2017).

The introduction of integrated development environments (IDEs) certainly helped to popularize online debuggers, and brought breakpoints, watchpoints, and step-through execution into the everyday workflow. Most of these concepts were already present in the earliest debuggers, as the 1966 survey by Evans and Darley (1966) shows.

Since debugging takes up so much of a developer's time, it is not surprising that computer scientists have tried to automate it as soon as the first bugs were discovered (Jacoby and Layton, 1961). This led to a wide range of

The terms *offline* and *post-mortem* still often get conflated.

attempts to design *automatic debuggers*, which are designed to automatically find and fix bugs. The term automatic debuggers has been used to describe both algorithmic debuggers (Shapiro, 1983), model checking, and tools for automatic fixing of bugs. However, in this dissertation we are interested in the more traditional *manual debuggers*.

Let us highlight a few techniques here, to illustrate the evolution and variety of manual debuggers.

Record-replay debuggers (Agrawal et al., 1991, Boothe, 2000, Burg et al., 2013, Feldman and Brown, 1988, O'Callahan et al., 2017, Ronsse and De Bosschere, 1999) allow offline debugging with a checkpoint-based trace, and have been widely studied. They have also been widely adopted in industry, with tools such as the RR framework (O'Callahan et al., 2017), which is one of the most advanced and widely used record-replay debugger to date.

Omniscient debuggers (Lewis, 2003, Pothier et al., 2007) takes this approach one step further, recording the entire execution of a program, allowing free offline exploration of the entire history, both backwards and forwards, and enabling advanced queries on causal relationships in the execution (Pothier and Tanter, 2009).

Omniscient debuggers are sometimes confusingly referred to as *time-travel debuggers*, *back-in-time debuggers*, or *reversible debuggers*. Unfortunately, these terms are not entirely interchangeable, as they can refer to very different techniques. For instance, some record-replay debuggers allow for backwards stepping as well, and are referred to by the same terms (Engblom, 2012).

Around 2016, several tailored debuggers were proposed for *reactive programming*, which visualize the data flows in the reactive program (Banken et al., 2018, Salvaneschi and Mezini, 2016). This is part of a slow shift towards more domain-specific debuggers, which are tailored to specific programming paradigms, or specific problems.

Likewise, *out-of-place debuggers* (Marra et al., 2018) were proposed to reduce debugging interference in big data applications. However, the technique is more widely applicable. In fact, it represents a new spectrum of debuggers that lie between remote and local debuggers, where a part of the remote debugging process is moved to a local process. This can reduce debugging interference, or—as this dissertation will show—reduce the performance overhead of remote debugging (Lauwaerts et al., 2022).

Of course the shift towards domain-specific debuggers, in no way meant that new general-purpose debuggers were not developed. A great example are *multiverse debuggers* (Torres Lopez et al., 2019), which emerged around the end of the last decade, as a powerful technique to debug non-determin-

istic program behavior. As the name suggests, multiverse debuggers allow programmers to explore multiple execution paths simultaneously, i.e., the multiverse of a program's execution.

Yet, the start of this decade saw many new domain-specific debugger techniques. For example, reversible debugging was recently adapted for *graphical programming languages*, by two projects for the Scratch language (Maloney et al., 2010), Blink (Strijbol et al., 2024) and NuzzleBug (Deiner and Fraser, 2024).

Only last year, a PhD thesis by Whitington presented a novel debugger solution for *functional programming*, which allows users to inspect the behavior of OCaml programs as they are interpreted (Whitington, 2024).

Another recent trend in debugger research is to use static analysis or model checking techniques in conjunction with debuggers, such as the *abstract debugger* by Holter et al. (2024) or the *symbolic debugger* by Karmios et al. (2023).

The list of debugging techniques and unique domains could go on for several more pages, and one could write a whole book about the history of debuggers. However, we hope the overview above provides sufficient context to the reader for now. In each following chapter, we will discuss the relevant related work in more detail, and highlight the differences with our own work.

1.4 How developers debug

Clearly, computer scientists recognized early on the potential of debuggers, not only for finding faults in programs, and helping to solve those faults—but also for understanding the programs themselves, and even for teaching and learning programming (Licklider and Clark, 1962). During the following decades, debugging was proven to indeed help with all these aspects (Spinelis, 2018, Steinert et al., 2009, Wilkin, 2025).

Still, debuggers have always remained somewhat in the shadows, with developers having a long tradition of avoiding debugging during software development. Many researchers have tried to understand why debuggers are avoided so much, and unsurprisingly, the causes are varied. The cognitive load of debugging is undeniable, and while it is by no means trivial to learn, few programmers are formally trained in debugging (McCauley et al., 2008, Perscheid et al., 2017). Many programmers are overconfident in the correctness of their code (Chattopadhyay et al., 2022), which leads to an unwillingness to examine their programs with the needed level of scrutiny (Calikli et al., 2010). Laziness cannot be discounted either, as debuggers are

often—perhaps rightly—perceived as hard to set up (Beller et al., 2018). In many cases programmers feel it is not worth the time to use debuggers for those mistakes they perceive as small or easy to diagnose (McCauley et al., 2008).

The unpopularity of debuggers among developers is not a new phenomenon. The situation was famously criticized thirty years ago by Henry Lieberman in his introduction to the 1997 special issue of Communications of the ACM, entitled “*The Debugging Scandal and What to Do About It*” with the words, “*Debugging is the dirty little secret of computer science*” (Lieberman, 1997), lamenting not just the unpopularity of debuggers, but the lack of attention and improvement they had received. Luckily, in the decades since, the research community has made tremendous strides. Yet to a certain extent, the situation remains unchanged in practice—especially in the domain of embedded software, where debuggers are still laborious to set up and industry adoption of research advances continues to lag behind.

1.4.1 Debugging without debuggers

Even when programmers avoid debuggers, they do still debug their code. Instead developers turn to print statement debugging (Beller et al., 2018), which is often seen as faster and easier at first, but can quickly lead to a slow and painful trial by error process.

Another interesting debugger-less debugging technique, is called *rubber duck debugging*, where programmers try and explain their code—possibly to a rubber duck—to help them understand the problem better (Hunt and Thomas, 1999).

While not without merit, debugging without the use of debuggers is often far too cumbersome, and can only get you so far given the complexity of the debugging task. Especially, print statement debugging, despite its popularity, should be considered bad practice for any serious debugging task. Even in the 1950s, computer systems already included breakpoints improving on print statement debugging by allowing programmers to debug live programs (Smith and Hurewitz, 1958). Since then, debuggers have come a long way.

1.4.2 Debugging with debuggers

Clearly not all errors, faults, or bugs can be found easily, let alone, be automatically detected and fixed. Many bugs are unpredictable, non-deterministic, and only emerge under specific conditions. This is especially true for software running on embedded systems, think of microcontrollers for hobbyist such as Arduino’s, or internet-of-things devices, such as smart thermostats, and

fitness trackers. Here, bugs can be caused not just by pure mistakes in the programming logic, but also by unexpected interactions with the hardware, specific timings, or unexpected behavior from the physical world. To track down the causes of such failures, we need direct access to the system's behavior—to stop execution, inspect memory, and walk through the precise state transitions that led to failure.

This is what debuggers can give us. They provide precise, and deterministic mechanisms for controlling and examining program execution, which is essential for diagnosing subtle bugs, concurrency issues, performance bottlenecks, and hardware-specific behavior. Ongoing debugger research not only enhances these capabilities but also drives advances in program analysis, visualization, security, and education.

While automatic tools such as static analyzers, model checkers, and type systems can catch many classes of errors, they are limited by what they are designed to check. They work when you know the kinds of mistakes you're guarding against. But when a system fails and you don't know why, and have no predefined property to verify, you need debuggers that let you observe the system directly.

1.4.3 Debugging constrained devices

Debuggers are especially useful in the domain of embedded systems, where software interacts heavily with hardware, and the physical world. These real-world interactions can lead to non-deterministic bugs that depend on specific input values, or other interactions with the environment. In fact, device issues are one of the most common causes of bugs in embedded systems (Makhshari and Mesbah, 2021). Additionally, embedded software is often written in an *interrupt-driven* manner, where the program is interrupted by hardware events, such as a timer or an external signal, and the program must respond to these events in real-time. Such code can be difficult to debug, as the program's state may change unexpectedly due to hardware interrupts, and the timing of these events can be unpredictable. Moreover, interrupt-driven code can lead to unpredictable concurrency bugs that depend on the order, interleaving, or timing of events, making them difficult to reproduce and diagnose (Li et al., 2023).

Unfortunately, debuggers for embedded software are often constrained by the very limitations of the hardware they target. They typically rely on specialized hardware debugging interfaces, which can be difficult to configure and require additional—sometimes expensive—equipment. This undoubtedly contributed to the fact that debuggers for embedded devices still lag behind advances in modern debugging techniques, offering only the most

basic operations, often limited only to simple breakpoints, stepping forward, and inspecting local variables—techniques that have been around since the 1960s. Consequently, debugging on embedded systems is frequently slow, cumbersome, and far less powerful than the tools available for general-purpose computing.

1.5 Roadmap

There is a clear need for novel debugging techniques that can address the unique challenges of debugging embedded systems. In this dissertation, we present a novel virtual machine for programming embedded devices, called *WARDuino*, on top of which we develop three novel debuggers for addressing the specific challenges of debugging embedded systems.

Chapter 2 1.5.1 Laying the foundations

The three novel debuggers presented in this dissertation, are described through formal semantics on top of which we provide our own correctness criteria. While common for programming languages, this is still too rarely done for debuggers. Yet, the benefits are the same. This motivated us to developed our own formal framework for describing remote debuggers as an answer to the following challenge.

C1 There are *no formal foundations* for how to develop good debuggers on constrained or unconstrained devices; neither how to describe their operations or what correctness could mean for these operations.

This challenge is revisited throughout the dissertation, as we present the different debuggers and their formal semantics, and most importantly our correctness criteria for these debuggers. However, we are conscious of the novelty and the complexity of our formalisations. Therefore we dedicate Chapter 2 of this book to present our formal framework as simply as possible before we delve into the real systems. We hope this chapter can help readers to more easily understand the following chapters.

1.5.2 Contributions to debugging of constrained devices

In chapters three, four and five we discuss our three novel debuggers. Each address several unique challenges. Some of these challenges are not exclusively tied to constrained systems, but represent broader scientific problems in debugging. However, each chapter is motivated by one or two larger challenges which tie the chapters together. We present each of these main challenges here as we sketch the outline of their associated chapter.

1.5.3 A remote debugger as a platform

Chapter 3

The first major challenge (**C2**) to developing a new generation of debuggers for constrained devices, is the lack of a modern development environment and easy instrumentation of the software. Instrumenting the software to be debugged, is a crucial prerequisite for any debugger. For constrained devices where software is usually written in low-level compiled languages such as C and C++, this is usually done with the help of a hardware debugger.

C2 Current embedded software development uses low-level compiled programming languages and bare-metal execution environments that make it difficult to instrument the software running on the constrained devices.

This challenge is addressed by our first contribution, a novel WebAssembly-based virtual machine for embedded devices, called *WARDuino*. By using a virtual machine, it becomes much easier to instrument the running code. In fact, in Chapter 3 we present a remote debugger on top of WARDuino. The WARDuino virtual machine and remote debugger form the perfect platform to quickly prototype and build new debugger techniques on.

However, this is far from the only contribution of Chapter 3. The remote debugger itself already improves much on the current development experience of most embedded developers.

C3 Current embedded software development is characterized by a cumbersome development experience due to low-level coding, lack of portability across platforms, slow deployment, hardware limitations, and limited debugger options.

In the first place the need to reflash the device after each change can slow down the development cycle significantly—especially, when developers use print statements to debug their code. Secondly, in case developers wish to use a debugger, they usually need to setup a hardware debugger, which can be cumbersome and time-consuming. Thirdly, embedded development is usually limited to low-level programming languages such as C and C++, where manual memory management presents additional work and challenges for the developers. We discuss these, and other lesser challenges underlying the slow development cycle in more detail in Chapter 3.

Chapter 3 shows how the WARDuino remote debugger reduces the need to reflash software, and enables traditional remote debugging without the need to use a hardware debugger. The chapter discusses the virtual machine in great detail, both its implementation and the formal semantics of its remote debugger. It likewise shows how using WebAssembly enables developers to use high-level languages to program embedded devices. Importantly, the

chapter highlights the components and design decisions that make WARDuino suitable as the basis for the novel debugging techniques we present in the following chapters.

Chapter 4

1.5.4 Overcoming constraints with out-of-place debugging

Limited memory and processing power are major concerns for embedded devices. The resource constraints not only impact the embedded programs, but also any debugger stub that is run alongside it.

C4 The *memory limitations* of embedded devices make it difficult to run debuggers alongside the target software, and the *processing constraints* prevent the adoption of more advanced debugging techniques.

To overcome this challenge (**C4**), we adapted the new stateful out-of-place debugging technique, which allows us to run most of the debugger on a separate device, while still debugging the target device. This reduces communication overhead and frees the debugger from the constraints of the target device. Chapter 4 shows exactly how we adapted the out-of-place debugging technique to embedded devices, and discusses the prototype built on top of the WARDuino virtual machine. As part of our research, we developed a novel out-of-place debugger that is able to handle stateful operations on non-transferable resources—a problem in out-of-place debugging that has not been addressed before. This lead to a novel *stateful out-of-place* debugger.

However, Chapter 4 has a secondary motivation. Software for embedded devices is often written using interrupts to ensures responsiveness even with harsh resource constraints, but the debugging of interrupt-driven programs is challenging. Traditional debuggers no longer have full control over the flow of execution, as interrupts let the program jump to seemingly arbitrary points. This can be very confusing for developers. Moreover, concurrency bugs can be caused by very specific interleaving of interrupts, which are difficult to reproduce and debug (Li et al., 2023). More generally, arbitrary interrupts can trigger at any time, leading to non-deterministic behavior, and making it difficult to reproduce bugs.

C5 Typical *interrupt-driven programs* interfere with live debugging processes by arbitrarily changing the execution flow of a program.

Chapter 4 shows how our novel out-of-place debugger addresses the third challenge (**C5**), by capturing all asynchronous events, such as hardware interrupts, and allowing the debugger to control when these events are dispatched.

Another major contribution of our novel out-of-place debugger, is the introduction of the first formal model of the technique. In Section 4.7, we prove the soundness and completeness of our stateful out-of-place debugging tech-

nique, which shows that the debugger does not interfere with the behavior of the program, despite the execution being distributed over two devices, and controlling of asynchronous events.

Finally, the stateful out-of-place debugger already allows for some control over the order and timing of asynchronous events, however, it does not fully address the difficulties associated with non-deterministic bugs, in particular, those bugs caused by very specific conditions of the environment.

1.5.5 Debugging non-deterministic I/O applications

Chapter 5

Non-deterministic bugs are very common on embedded systems, but are notoriously difficult to debug, as they often depend on the specific timing or order of events, on very specific input, or environmental conditions.

C6 Current embedded debuggers are not equipped to *debug non-deterministic bugs* caused by their I/O intensive nature.

This shortcoming is addressed by our multiverse debugger for microcontrollers, *MIO*, which we present in Chapter 5. The *MIO* debugger presents the first multiverse debugger that works on a live execution of the program. This brings with it a number of challenges, foremost is how to take into account both input and output streams during live exploration of the multiverse. While highly motivated by the embedded software setting, this challenges is not unique to constrained devices, but applies more generally to multiverse debugging as a principle.

C7 How can multiverse debugging be applied to concrete executions and enable live exploration of the multiverse in the presence of I/O?

The *MIO* debugger is unique in solving this issue by reversing both the program's execution and its output effects, while remaining sound and complete. Again, we prove the soundness and completeness of our multiverse debugger, particularly in Section 5.3.9.

1.5.6 Open-source prototype and usability

A major goal throughout this research has been to develop usable prototypes of our novel debugging techniques. Prototypes which can debug real-world embedded software, thereby showing the feasibility of our techniques, and increasing the chances of their adoption. Towards this end, all our prototypes are open-source, and available on GitHub, alongside a dedicated documentation website.

Chapter 6 1.5.7 Using debuggers for Testing

No software can be considered usable—even as a prototype for other researchers—without proper testing. Unfortunately, typical regression testing as part of continuous integrations, as is now standard practice, is not common in embedded software development. Furthermore testing frameworks are rarely adapted for testing embedded software, and suffer from many of the same limitations as debuggers due to the resource constraints of the target devices. Additionally, testing debuggers comes with its own challenges and specific requirements, not met by typical testing frameworks.

In other words, while developing our novel debugger prototypes, we increasingly found ourselves in need of a new, dedicated testing framework for embedded software. Therefore, we developed our own testing framework for large-scale testing on constrained devices, called *Latch*, which implements a novel testing approach we call *managed testing*. We will discuss this framework in detail at the end of the dissertation in Chapter 6.

Chapter 7 1.5.8 Reflections on the Future

To conclude this dissertation we reflect in Chapter 7 on the lessons learned over the course of almost four years of research, and look ahead to what future research in this area may cover.

Chapter 2

Foundations for Debugging Techniques

*Beware of bugs in the above code;
I have only proved it correct, not tried it.*
— Donald Knuth, personal communication c. 1970

A central concern of this dissertation is the design of debuggers, and what makes a good debugger. To understand and answer this question, there are currently few formal foundations to build upon. Any such foundation must answer the fundamental question of what constitutes correctness for debuggers. Over the course of writing this dissertation, several correctness criteria for our debuggers emerged, the essence of which we distill in this chapter into two fundamental correctness criteria for the operations of manual online debuggers.

2.1 Semantics of debuggers

Before we can begin to reason about the correctness of manual online debuggers, we need to establish their formal semantics. Unfortunately, defining the semantics of debuggers has always received less attention than formalizations for programming languages or compilers (da Silva, 1992). This lack of interest, has resulted in quite a sparse collection of existing semantics, which focus on very different aspects, and are defined in very different ways. To this day, there is no clear consensus on what constitutes correctness for debuggers, or even, which are the essential aspects for a tool to fall under the broad category of debuggers.

Whether or not such a consensus is possible is an interesting question in itself. This is not the focus of this dissertation, but we are interested in what constitutes correctness for the operations of manual debuggers. We believe that the soundness and completeness criteria we define in this chapter are a good starting point for defining correctness for such debuggers.

2.1.1 A brief history of formal debuggers

To our knowledge, the earliest attempt at formally defining a debugger-like system is by Bahlke and Snelting (1986). The paper presents the *Programming*

System Generator, which is a programming tool that generates an interpreter from the denotational semantics of a programming language. It supports interactive evaluation with the ability to inspect or redefine code, which is somewhat debugger-like in spirit.

However, the earliest work we are aware of—that formally describes a tool we would today recognize as a debugger—is the PhD thesis by da Silva (1992). It defines debuggers as any tool that can dynamically give some information of the intermediate states of program evaluation, on the request of the user. A definition not unlike the one we use in this dissertation. The thesis presents a way of formalizing debuggers using structural operational semantics, but the formalism does not separate the language semantics from the debugger semantics.

In 1995, Bernstein and Stark (1995) improved on this approach by explicitly separating the language and debugger operations in their formalisation, allowing them to define the debugger semantics in terms of the language semantics. To our knowledge they are the first to use this approach.

Another early attempt used PowerEpsilon (Zhu and Wang, 1992, 1991) to describe the source mapping used in a debugger as a denotational semantics for a toy language that can compile to a toy instruction set (Zhu, 2001). While an interesting formalization, it does not say anything about the debugging operations themselves or their correctness.

A more recent work by Li and Li (2012) focussed on automatic debuggers. Its formalization is based on a kernel of the C language, and defines operational semantics for tracing, and for backwards searching based on those traces. The work proves that its trace and search operations terminate, but defines no general correctness criteria.

However, most works after 2000 have largely used the approach first presented by Bernstein and Stark (1995), such as a number of recent works (Ferrari and Tuosto, 2001, Holter et al., 2024, Lauwaerts et al., 2024, Torres Lopez et al., 2017) that inspired and informed this dissertation. While there are still large differences in the way debuggers are formalised in recent works, it is clear that defining their semantics in terms of the underlying language is now accepted as the canonical approach.

By defining the operational semantics of a debugger in terms of the underlying language, it becomes much easier to reason about the correctness of the debugger, since the correctness can be stated in terms of the underlying language. In hindsight, this may seem an obvious solution to the reader, but that speaks to the fact that this is by far the best and most intuitive approach to take. As we are highly interested in the possible correctness criteria of debuggers in this dissertation, we will use this approach throughout.

Simply using the underlying language in an operational semantics—as an approach—still leaves a lot of flexibility in how to define the semantics of the debugger. Therefore, we will present this thesis’ approach in more detail in this chapter, as we simultaneously discuss our general correctness criteria.

2.1.2 Four debuggers, four semantics

Given the wide variety of debuggers, we will present our formal framework—for debugger semantics and their correctness—by discussing four different debuggers with each their own semantics. The last debugger serves as a counterexample, illustrating a common type of debugger that is complete but not sound. Importantly, the semantics follow the same general design—presenting the overall formal framework we use in this dissertation.

Looking slightly ahead, we will define the following four debuggers, which always build on top of the previous one:

Debugger	Description
λ_D^*	A tiny remote debugger, presenting a smallest working example.
λ_D^\rightarrow	A remote debugger with support for the most conventional debug operations.
λ_D^\leftarrow	A reversible debugger, which can step backwards in time.
λ_D^\leftarrow	<i>Counterexample.</i> An intercession debugger, which can change the program at runtime.

The four debuggers allow us to introduce different aspects of our formal framework step by step. The semantics in this chapter, are blueprints for the more complex semantics we discuss later in this dissertation. They also serve to illustrate the general correctness criteria we define for our debuggers.

In order to present our formal framework, we need a simple yet illustrative language. Fortunately there is a straightforward choice, the *simply typed lambda calculus* (λ^\rightarrow), proposed by Church (1940). Most readers will be familiar with the simply typed lambda calculus, but for those who are not, we provide a brief introduction.

While heavy in formal aspects, this chapter serves as a—hopefully somewhat gentle—introduction into the formal foundations of this dissertation.

2.2 λ^\rightarrow as the running example

The simply typed lambda calculus, is arguably the simplest, and most well-known formal system used to study computation and programming languages. For fullness, we provide the core rules for the simply typed

Syntax	Evaluation	$t \rightarrow t'$
$t ::=$ x $\lambda x : T.t$ $t t$	(terms) variable abstraction application	$\frac{t_1 \rightarrow t'_1}{t_1 t_2 \rightarrow t'_1 t_2}$ $\frac{t_2 \rightarrow t'_2}{v_1 t_2 \rightarrow v_1 t'_2}$
$v ::=$ $\lambda x : T.t$	(values) abstraction	$(\lambda x : T_{11}.t_{12}) v_2 \rightarrow [x \mapsto v_2] t_{12}$
$T ::=$ $T \rightarrow T$	(types) function type	Typing $\frac{x : T \in \Gamma}{\Gamma \vdash x : T}$
$\Gamma ::=$ \emptyset $\Gamma, x : T$	(contexts) empty context variable binding	$\frac{\Gamma, x : T_1 \vdash t_2 : T_2}{\Gamma \vdash \lambda x : T_1. t_2 : T_1 \rightarrow T_2}$ $\frac{\Gamma \vdash t_1 : T_{11} \rightarrow T_{12} \quad \Gamma \vdash t_2 : T_{11}}{\Gamma \vdash t_1 t_2 : T_{12}}$

The rules for λ^\rightarrow , in both Figure 2-1 and Appendix A, are taken from the definitive work, *Types and Programming Languages* from Benjamin C. Pierce.

Figure 2-1. Pure simply typed lambda calculus λ^\rightarrow . The syntax, evaluation, and typing rules for the simply typed lambda calculus with no base types (Pierce, 2002).

lambda calculus without any base types in Figure 2-1. In the lambda calculus, functions are the central form of computation, and there are only two basic operations; function application, and function abstraction. Function application is used to apply a function to another, while abstraction binds free variables to the function. In the simply typed version, each expression is assigned a type, and functions are given types that describe the kinds of inputs they accept and outputs they produce.

2.3 λ_D^* : A tiny remote debugger for λ^\rightarrow

We start by defining the syntax of a tiny remote debugger for λ^\rightarrow with booleans and natural numbers, defined as Peano numbers (Kennedy, 1974, Peano, 1891). The complete set of syntax, evaluation, and typing rules for booleans and natural numbers for λ^\rightarrow can be found in Appendix A. Because the debuggers we discuss in this dissertation are each debuggers for distributed systems, and therefore remote debuggers of a kind, we start with a simple remote debugger. The easiest way to define such a debugger is as a distributed system with a *client* and a *server*.

The rules for our tiny remote debugger are shown in Figure 2-2—these rules define the remote debugger as a distributed system with a *client* and a *server*; respectively, modeling the debugger frontend and backend. In the

remote debugger, the only role of the client is to supply input from the user, and displaying the output from the debugger. We model these interactions with the outside world through a simple messaging system, where messages arrive in order, one by one, in a message box. The server communicates with the client through an identical message box system, and is responsible for performing the debug commands it receives.

The evaluation rules in Figure 2-2 are split into three sets, the server debugging steps (\longrightarrow_s), the client steps (\longrightarrow_c), and the global steps of the remote debugger ($\longrightarrow_{\mathbb{D}}$), which wraps the server and client steps.

2.3.1 The syntax rules of the $\lambda_{\mathbb{D}}^*$ debugger

The steps of the remote debugger $\longrightarrow_{\mathbb{D}}$ are defined over a configuration $c \mid s$, where we have respectively, the state of the debugger client, and the state of the debugger server.

The configuration of the client is split into two message boxes, (1) the input from the user comprising of the *debug commands* (m_c), and (2) the output received from the server (m_s). Message boxes are our way of modeling both inter-process and intra-process communication. In the case of the client, the message box m_c models the intra-process communication from user to frontend (client), and the second message box m_s models the intra-process communication from backend (server) to frontend (client).

The configuration of the server is similar, but now contains the current term t of the program being debugged, alongside its two message boxes. The message boxes in the server are used to model the inter-process communication between the debugger backend and the debugger frontend. The debugger server can return as output to the client, either a snapshot of the program, or an acknowledgement of a debug command, otherwise the box is empty (\emptyset). The debug commands supported by the debugger are *step* and *inspect*—to take a simple step in the program, and to inspect the current state of the program. When there is no next command in the message box, we write (\emptyset).

2.3.2 The evaluation rules of the $\lambda_{\mathbb{D}}^*$ debugger

The entire evaluation of the debugger ($d \longrightarrow_{\mathbb{D}} d'$) is captured by only eight rules. The first three steps are server steps, which describe the operation of the debugger backend.

Step When the current term t can reduce to t' , then the debugger can take a step to t' , and output an acknowledgement of the successful step.

Internal in this context refers to the place where the program is running.

Syntax	<i>Server evaluation</i>	
$d ::= c \mid s$ <i>(global debugger)</i>	$\frac{t \longrightarrow t'}{\langle step, \emptyset ; t \rangle \longrightarrow_s \langle \emptyset, \text{ack step} ; t' \rangle}$	$s \longrightarrow_s s'$ <i>(Step)</i>
$s ::= m_c, m_s ; t$ <i>(server)</i>	$\frac{}{\langle step, \emptyset ; v \rangle \longrightarrow_s \langle \emptyset, \text{ack } \emptyset ; v \rangle}$	<i>(Fallback)</i>
$c ::= m_c, m_s$ <i>(client)</i>	$\frac{}{\langle inspect, \emptyset ; t \rangle \longrightarrow_s \langle \emptyset, \text{snap } t ; t \rangle}$	<i>(Inspect)</i>
$m_s ::= \emptyset \quad \text{nothing}$ $\text{snap } t \quad \text{term}$ $\text{ack } m_c \quad \text{acknowledgement}$	$\frac{}{\langle m_c, m_s \rangle \longrightarrow_c \langle m_c, \emptyset \rangle}$	$c \longrightarrow_c c'$ <i>(Process)</i>
$m_c ::= \emptyset \quad \text{nothing}$ $\text{step} \quad \text{single step}$ $\text{inspect} \quad \text{inspection}$ <i>(debug commands)</i>	$\frac{\langle m_c, \emptyset \rangle \mid \langle \emptyset, \emptyset ; t \rangle}{\longrightarrow_D \langle \emptyset, \emptyset \rangle \mid \langle m_c, \emptyset ; t \rangle}$	$d \longrightarrow_D d'$ <i>(Input)</i>
<i>Initial configuration</i>	$\frac{\langle m_c, \emptyset \rangle \mid \langle \emptyset, m_s ; t \rangle}{\longrightarrow_D \langle m_c, m_s \rangle \mid \langle \emptyset, \emptyset ; t \rangle}$	<i>(Output)</i>
$d_{\text{start}} = \langle \emptyset, \emptyset \rangle \mid \langle \emptyset, \emptyset ; t_{\text{start}} \rangle$	$\frac{c \longrightarrow_c c'}{c \mid s \longrightarrow_D c \mid s}$	<i>(Client)</i>
	$\frac{s \longrightarrow_s s'}{c \mid s \longrightarrow_D c \mid s}$	<i>(Server)</i>

Figure 2-2. Remote debugger semantics λ_D^* . The syntax and evaluation rules for a simple remote debugger (\longrightarrow_D) for the simply typed lambda calculus λ^\rightarrow with natural numbers and booleans.

Fallback This fallback rule allows the debugger to drop *step* messages in case there is no $t \longrightarrow t'$. For the λ^\rightarrow , this means that the term must be a value v . In this case, we output an empty acknowledgement, to indicate that the command was processed, but did not have any effects.

Inspect The inspect step outputs a snapshot of the current term t .

To lift these server steps to describe the operation of a remote debugger, we only need to describe how they interact with the client, or debugger backend. The rest of the rules are therefore mostly concerned with how input and

output are processed. We model the debugger frontend with a single client rule, *Process*.

Process The client takes the server message m_s from its input message box, and replaces it with \emptyset , indicating that the output was used to update the user interface.

The evaluation of the remote debugger is informed by the commands that arrive in the input message box, a debug session can therefore be seen as a series of remote steps ($d \xrightarrow{\mathbb{D}}^* d'$) that are the result of a sequence of debug commands, which we write as (m_c^*) . The final four global rules describe how this works.

Input Whenever the client receives a m_c from the user, it is send to the input message box of the server, and the input message box of the client is updated to \emptyset . It is then ready to receive the next command.

Output Whenever the server has a m_s in its output message box, it is send to the client, and the message is cleared from the server's message box.

Client Whenever a client rule applies, the client in d can take a step.

Server Analogously, whenever a server rule applies, the server in d can take a step.

Now that we have the formal semantics for a remote debugger that can step through and inspect a λ^\rightarrow program, we can define what correctness means for such a debugger.

2.3.3 Correctness criteria for the $\lambda_{\mathbb{D}}^*$ debugger

Since we define our debugger in terms of the underlying language, the most intuitive definition of correctness for a debugger is that it should not change the semantics of the program being debugged. This intuition is shared by the earliest works on debugger correctness such as da Silva (1992). We develop the idea into two correctness criteria, *debugger soundness* and *debugger completeness*.

Debugger soundness demands that for any debug session that begins at the start of the program, there is a path in the underlying language semantics that leads to the same final program state. In the theorem, we use the shorthand notation t_d to denote the current term of a debugging configuration d .

Theorem 2-1. (Debugger soundness) Let d_{start} be the initial configuration of the debugger for some well-typed program t . Then:

$$\forall d . (d_{\text{start}} \xrightarrow{*_{\mathbb{D}}} d) \implies (t \xrightarrow{*} t_d) \wedge t_d \in d$$

Proof sketch. The proof proceeds by induction on the number of steps taken in the debugger. Since *Step* is the only rule that changes the term t in the debugger configuration, and *Step* uses the internal step ($\xrightarrow{*}$); there is necessarily a path $t \xrightarrow{*} t_d$ in the underlying language semantics. \square

Debugger completeness is the dual of soundness, but in the opposite direction. Completeness demands that any path in the underlying semantics can be observed in the debugger.

Theorem 2-2. (Debugger completeness) Let t be a well-typed λ^{\rightarrow} program, and d_{start} the start configuration of a debug session for this program. Then:

$$\forall t' . (t \xrightarrow{*} t') \implies \exists d . (d = \langle \emptyset, \emptyset \rangle \mid \langle \emptyset, \emptyset ; t' \rangle) \wedge (d_{\text{start}} \xrightarrow{*_{\mathbb{D}}} d)$$

Proof sketch. Given any path $t \xrightarrow{*} t'$ in λ^{\rightarrow} , we can construct a sequence of debug commands m_c^* to be the exact number of *step* commands corresponding to the path in λ^{\rightarrow} . Then the debug session starting in d_{start} with the commands m_c^* will take the exact same path by construction (see rule *Input* and *Step*), resulting in a configuration $\langle \emptyset, \emptyset \rangle \mid \langle \emptyset, \emptyset ; t' \rangle$. \square

Debugger soundness and completeness together ensure that the debugger does not deviate from the semantics of the program being debugged, and that the debugger and the normal execution observe the same program behaviour. This is an essential property for any type of debugger.

Both theorems are trivial to prove for our tiny remote debugger $\lambda_{\mathbb{D}}^*$, however, this by no means implies that they are trivial to prove for every debugger, or that they are not valuable guarantees. To illustrate the usefulness of the correctness criteria, we will discuss them for a two interesting debuggers built on our tiny remote semantic.

2.4 $\lambda_{\mathbb{D}}^*$: A conventional debugger for λ^{\rightarrow}

The tiny remote debugger $\lambda_{\mathbb{D}}^*$ is perhaps too simple to be really considered —what we conventionally call—a live remote debugger. The most obvious

New syntactic forms

$s \equiv$	(server)	$m_s \equiv$	(server messages)
	$\langle m_c, m_s, n, e, b ; t \rangle$...	breakpoint hit
$e \equiv$	(execution state)	$m_c \equiv$	(debug commands)
paused	paused state
play	unpaused state	play	unpause
$b \equiv$	(breakpoints)	pause	pause
\emptyset	empty	bp ⁺ (n)	add breakpoint
n, b	list of numerics	bp ⁻ (n)	remove breakpoint

Numericals from λ^{\rightarrow}	New initial configuration
$n \equiv$	$d_{\text{start}} = \langle \emptyset, \emptyset \rangle \mid \langle \emptyset, \emptyset, 0, \text{paused}, \emptyset ; t_{\text{start}} \rangle$
0	constant zero
$\text{succ } n$	succ

Figure 2-3. Syntax rules of the conventional live debugger $\lambda_{\mathbb{D}}^{\rightarrow}$. The syntax rules for *pause*, *play*, and *breakpoints* for the $\lambda_{\mathbb{D}}^*$ debugger semantics. Changes to existing rules are highlighted.

missing pieces are *pause* and *play* commands, and support for *breakpoints*. The semantics so far consider the program to be paused at all times, and the debugger only moves forward when the user issues a *step* command.

To support the pausing of the program’s evaluation, as well as breakpoints, we extend the syntax of the tiny remote debugger with the rules shown in Figure 2-3. The internal debugger configuration is extended with a *program counter*, a plain numerical value as defined by the syntax of λ^{\rightarrow} , an *execution state* that can either be *paused* or *play*, and a set of *breakpoints*.

Using these three new fields (n, e, b), we can define the new evaluation rules for the conventional debugger. Figure 2-4 shows the new evaluation rules added to or replacing the existing rules. The full set of rules for the conventional debugger are shown in Appendix B.

Now, we can easily let the debugger stop at any point in the reduction of the λ^{\rightarrow} program by adding a rule for normal unpause execution (*Run*) and by adding two rules to change the execution state to either *paused* or *play*. For breakpoint support we need to keep track of a program counter, which for the λ^{\rightarrow} can simply be a numerical value that counts the number of reductions. To increase the counter correctly, we only need to change the *Step* and *Run* rules to increment the counter by one for every reduction in the λ^{\rightarrow} . Lastly,

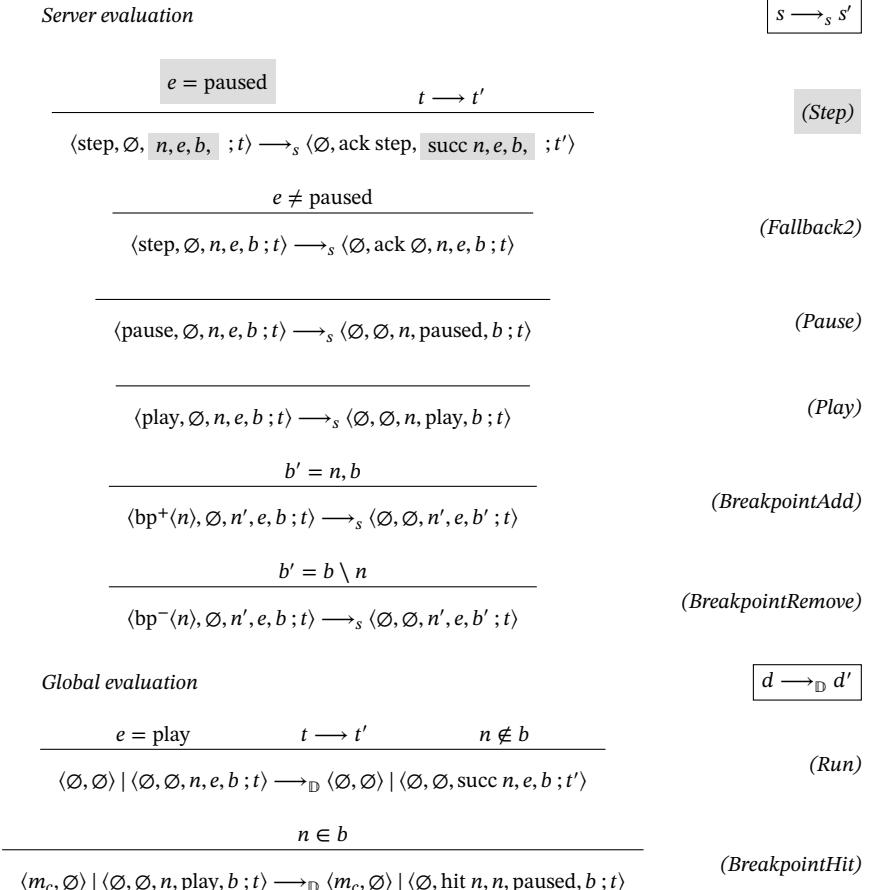


Figure 2-4. Evaluation of conventional live debugger operations for $\lambda_{\mathbb{D}}$. The evaluation rules for *pause*, *play*, and *breakpoints* for the $\lambda_{\mathbb{D}}^*$ debugger semantics. Changes to existing rules are highlighted.

we need to add two new rules to add and remove breakpoints from the set of breakpoints in the debugger configuration, and an extra fallback rule to handle the case where the debugger is not paused, but a step command is received.

All other rules from the tiny remote debugger remain unchanged, apart from the additional fields in the configuration. The exact values of these fields are immaterial for those remaining rules, except for any changes shown in Figure 2-4.

Step The *Step* rule now only applies when the debugger is in the paused state.

Fallback2 We add a second fallback rule, for when a step command is received, but the debugger is not paused. The execution state is irrelevant in the other fallback rule.

Pause The *Pause* rule changes the execution state to *paused*.

Play The *Play* rule changes the execution state to *play*.

BreakpointAdd The *BreakpointAdd* rule adds the breakpoint n from the $(bp^+\langle n \rangle)$ command to the set of breakpoints in the debugger configuration.

BreakpointRemove The *BreakpointRemove* rule removes the breakpoint n —specified by the $(bp^-\langle n \rangle)$ command—from the set of breakpoints in the debugger configuration.

Run When the execution state is *play*, and there are currently no commands in the message box of the client or server, nor is the current program counter n an element of the breakpoints set b , then the debugger will take a single step in the underlying language semantics $t \rightarrow t'$. Through this rule the debugger will continue normal execution until it reaches a breakpoint, or the program is paused, or the program cannot be reduced anymore.

BreakpointHit When the execution state is *play*, and the program counter n is part of the breakpoint set b , the debugger pauses the program by changing the execution state to *paused*. Finally, it outputs an alert of the breakpoint hit containing the current program counter.

2.4.1 Correctness criteria for the $\lambda_{\mathbb{D}}^{\rightarrow}$ debugger

We will apply the same *soundness* and *completeness* criteria to the conventional debugger as we did for the tiny remote debugger. We briefly sketch the proofs here. We start with soundness, since its theorem remains unchanged.

Proof sketch. (Debugger soundness for $\lambda_{\mathbb{D}}^{\rightarrow}$) The proof proceeds by induction on the number of steps taken in the debugger. The *Step* and *Run* rules are the only rules that changes the term t in the debugger configuration, and both use the λ^{\rightarrow} step (\rightarrow). This means that there is necessarily a path $t \xrightarrow{*} t_d$. \square

For completeness, we tweak the formulation of the theorem slightly, for the new components of the server configuration.

Theorem 2-3. (Debugger completeness for λ_D^\rightarrow) Let t be a well-typed λ^\rightarrow program, and d_{start} the start configuration of a debug session for this program. Then:

$$\begin{aligned} \forall t' . (t \xrightarrow{*} t') \implies \\ \exists d . (d = \langle \emptyset, \emptyset \rangle \mid \langle \emptyset, \emptyset, n, \text{paused}, b ; t' \rangle) \wedge (d_{\text{start}} \xrightarrow{*}_D d) \end{aligned}$$

Given the construction of our debugger semantics it remains easy to construct a sequence of debug commands that follows the exact same path as the underlying language semantics.

Proof sketch. (Debugger completeness for λ_D^\rightarrow) We can construct a sequence of *step* commands equal to the number of steps in the path $t \xrightarrow{*} t'$. Starting from d_{start} , the debugger will apply the *Input*, *Step*, *Process* steps repeatedly until all these commands have been consumed. Afterwards, the state of debugger is $\langle \emptyset, \emptyset \rangle \mid \langle \emptyset, \emptyset, n, \text{paused}, b ; t' \rangle$. \square

2.5 λ_D^\leftarrow : A reversible debugger for λ^\rightarrow

Another interesting extension to the tiny remote debugger, is to turn it into a reversible debugger (Engblom, 2012). We start from the conventional debugger semantics in Section 2.4, and add a *backwards step* command.

A common approach to implementing a reversible debugger is to periodically store snapshots of the program state, and reconstruct the execution from the last snapshot (Engblom, 2012, Klimushenkova and Dovgalyuk, 2017). These type of reversible debuggers are often called *reconstruction-based reversible debuggers* (Engblom, 2012). Formalising this approach requires only few extensions to the semantics of the conventional debugger. We list the new syntax and evaluation rules for the reversible debugger in Figure 2-5.

We extend the syntax of the debugger server with a list of snapshots, which are tuples of program counters and terms. The commands are extended with a *backwards step* command, which takes a single step backwards in the program. To handle this command we need five additional server rules, specifically, the *BackwardStep0*, *BackwardStep1*, and *BackwardStep2* rules, along with two fallback rules.

BackwardStep0 The *BackwardStep0* rule applies when the program counter is not zero, but only the start snapshot is present in the snapshot list. In this case the program reduces n times starting from the initial configuration, to arrive exactly one reduction before the current term t .

New syntactic forms

$s \equiv$	$(server)$	$z \equiv$	$(snapshots)$
	$(m_c, m_s, n, e, b, z ; t)$	$(0, t)$	$start\ snapshot$
		$(n, t), z$	$list\ of\ snapshots$
$m_c \equiv$	$(debug\ commands)$		
	\dots		
	$step^{\leftarrow}$	$backwards\ step$	

Server evaluation

$$s \longrightarrow_s s'$$

$$\frac{z = (0, t') \quad e = \text{paused} \quad t' \longrightarrow^n t''}{(\text{step}^{\leftarrow}, \emptyset, \text{succ } n, e, b, z ; t) \longrightarrow_s (\emptyset, \text{ack step}^{\leftarrow}, n, e, b, z ; t'')} \quad (\text{BackwardStep0})$$

$$\frac{n \neq n' \quad z = ((n', t'), z') \quad e = \text{paused} \quad t' \longrightarrow^{n-n'} t''}{(\text{step}^{\leftarrow}, \emptyset, \text{succ } n, e, b, z ; t) \longrightarrow_s (\text{ack step}^{\leftarrow}, \emptyset, n, e, b, z ; t'')} \quad (\text{BackwardStep1})$$

$$\frac{z = ((n, t'), z') \quad e = \text{paused}}{(\text{step}^{\leftarrow}, \emptyset, \text{succ } n, e, b, z ; t) \longrightarrow_s (\emptyset, \text{ack step}^{\leftarrow}, n, e, b, z' ; t')} \quad (\text{BackwardStep2})$$

$$\frac{e \neq \text{paused}}{(\text{step}^{\leftarrow}, \emptyset, n, e, b, z ; t) \longrightarrow_s (\emptyset, \text{ack step}^{\leftarrow}, \emptyset, n, e, b, z ; t')} \quad (\text{BackwardFallback1})$$

$$\frac{z = (0, t)}{(\text{step}^{\leftarrow}, \emptyset, 0, e, b, z ; t) \longrightarrow_s (\emptyset, \text{ack step}^{\leftarrow}, \emptyset, 0, e, b, z ; t')} \quad (\text{BackwardFallback2})$$

Global Evaluation

$$d \longrightarrow_{\mathbb{D}} d'$$

$$\frac{e = \text{play} \quad t \longrightarrow t' \quad z' = ((\text{succ } n, t'), z) \quad n \notin b \quad (\text{succ } n) \% \theta = 0}{(\emptyset, \emptyset) \mid (\emptyset, \emptyset, n, e, b, z ; t) \longrightarrow_{\mathbb{D}} (\emptyset, \emptyset) \mid (\emptyset, \emptyset, \text{succ } n, e, b, z' ; t')} \quad (\text{Run1})$$

$$\frac{e = \text{play} \quad t \longrightarrow t' \quad n \notin b \quad (\text{succ } n) \% \theta \neq 0}{(\emptyset, \emptyset) \mid (\emptyset, \emptyset, n, e, b, z ; t) \longrightarrow_{\mathbb{D}} (\emptyset, \emptyset) \mid (\emptyset, \emptyset, \text{succ } n, e, b, z ; t')} \quad (\text{Run2})$$

Figure 2-5. Syntax and evaluation rules of the reversible debugger $\lambda_{\mathbb{D}}^{\leftarrow}$.
The semantics of $\lambda_{\mathbb{D}}^{\leftarrow}$ extend the conventional debugger semantics $\lambda_{\mathbb{D}}^{\rightarrow}$, shown in Figure 2-3 and Figure 2-4.

BackwardStep1 The *BackwardStep1* rule applies reduces the program counter by one, and reduces the term t' from the last snapshot exactly $n - n'$ times, to the term t'' .

BackwardStep2 The *BackwardStep2* rule applies when the program counter is exactly one higher than the program counter of the last snapshot. In this case, the debugger only restores the snapshot and removes it from the snapshot list.

BackwardFallback1 The *BackwardFallback1* rule applies when the execution state is not paused. Analogous to the forward step, the debugger will not step back if the program is not paused, and simply send an empty acknowledgement to indicate that nothing has changed.

BackwardFallback2 The *BackwardFallback2* rule applies when the program counter is zero, in this case, the only sensible option is to return an empty acknowledgement, since the program cannot step back any further.

Given these server evaluation rules, we only need to specify in the global evaluation rules how and when snapshots are created. Several strategies can be used to determine when to create new snapshots, for simplicity we will let the debugger create a snapshot every few steps by replacing the *Run* rule by the following two rules.

Run1 We change the *Run* rule to add a new snapshot to the list z whenever the program counter is a multiple of θ , which we consider a static configuration of the debugger.

Run2 In case the program counter is not a multiple of θ , the *Run2* rule is the same as the original *Run* rule.

To summarize the reversible semantics, when the reversible debugger is at a term t with program counter $\text{succ } n$, then to step back once, it will restore the last snapshot and take exactly $n - n'$ steps where n' is the program counter of the snapshot.

2.5.1 Correctness criteria for the λ_D^\leftarrow debugger

Again, we apply the same soundness and completeness criteria to the reversible debugger as we did for the two previous debuggers. The proofs however, are slightly more involved, since we need to reason about the snapshots. To make this easier, we will first prove a lemma about the snapshots that is helpful in the proof of soundness.

The value of θ could be changed through some meta-rules for the debugger.

Lemma 2-1. (Snapshot preservation) The semantics of a reconstruction-based reversible debugger is said to be *snapshot preserving* if the following holds:

$$\begin{aligned} \forall d . d = c \mid \langle m_c, m_s, n, e, b, z ; t \rangle \wedge d_{\text{start}} &\xrightarrow{*_{\mathbb{D}}} d \\ \iff \forall (n', t') \in z . n' \leq n \wedge t_{\text{start}} &\xrightarrow{*} t' \end{aligned}$$

Informally, the lemma states that for any debugger configuration d that is reachable from the start configuration d_{start} , all snapshots in the debugger must contain a term t that is reachable from the start state t_{start} , and n has a program counter lower or equal to the current program counter. Or in other words, snapshots in a debugging session contain only reachable states, from the past.

Proof sketch. (Snapshot preservation for $\lambda_{\mathbb{D}}^{\leftarrow}$) The proof is straightforward by induction on steps taken in the debug session ($\xrightarrow{*_{\mathbb{D}}}$). In the base case, this is always trivial to prove by construction. In the inductive case, each case is straightforward to prove given the induction hypothesis. \square

Given Lemma 2-1, we know that a snapshot list never contains any impossible program states, and that there is never a snapshot that lies in the *future* of the current program state.

Proof sketch. (Debugger soundness for $\lambda_{\mathbb{D}}^{\leftarrow}$) The proof proceeds by induction over the steps taken in the debug session. Except for the new backward stepping rules, the cases proceed analogous to the proof for $\lambda_{\mathbb{D}}^{\rightarrow}$. Given the induction hypothesis and Lemma 2-1, the backward rules *BackwardStep0*, *BackwardStep1*, and *BackwardStep2* are straightforward to prove. \square

For completeness, we tweak the formulation of the theorem slightly, for the new components of the server configuration.

Theorem 2-4. (Debugger completeness $\lambda_{\mathbb{D}}^{\leftarrow}$) Let t be a well-typed λ^{\rightarrow} program, and d_{start} the start configuration of a debug session for this program. Then:

$$\begin{aligned} \forall t' . (t \xrightarrow{*} t') \implies \\ \exists d . (d = \langle \emptyset, \emptyset \rangle \mid \langle \emptyset, \emptyset, n, \text{paused}, b, z ; t' \rangle) \wedge (d_{\text{start}} \xrightarrow{*_{\mathbb{D}}} d) \end{aligned}$$

<i>New syntactic forms</i>	<i>Server evaluation</i>	$s \xrightarrow{s} s'$
$m_c ::= \dots$ $\quad \quad \quad (commands)$ $\quad \quad \quad \dots$ $\quad \quad \quad \text{subst } t_1 t_2 \quad \text{substitute}$	$\frac{\Gamma \vdash t_2 : T' \quad \Gamma, t_1 : T' \vdash t : T}{\langle \text{subst } t_1 t_2, \emptyset, n, e, b, z ; t \rangle}$	$\xrightarrow{s} \langle \emptyset, \text{ack subst } t_1 t_2, n, e, b, z ; [t_1 \mapsto t_2] t \rangle$

Figure 2-6. Intercession debugger semantics extending $\lambda_{\mathbb{D}}^*$.

Proof sketch. We can construct a sequence of *step* commands equal to the number of steps in the path $t \xrightarrow{*} t'$. Starting from d_{start} , the debugger will apply the *Input*, *Step*, *Process* steps repeatedly until all these commands have been consumed. Afterwards, the state of debugger is $\langle \emptyset, \emptyset \rangle \mid \langle \emptyset, \emptyset, n, \text{paused}, b, z ; t' \rangle$. \square

2.6 A counterexample: an intercession debugger for λ^{\rightarrow}

Our debuggers so far have only observed the execution of a program, without interceding in it. Even our reversible debugger, does not intercede in the control flow of the program, it only replays a previously observed execution. Yet, it is quite common for debuggers to support changing the value of variables (Stallman et al., 1988), or influence the control flow of the program (“Alter the Program’s Execution Flow,” 2024, Lauwaerts et al., 2022, Stallman et al., 1988). In this work, we refer to these as *intercession debuggers*.

Intercession debuggers are an interesting case to study in terms of our correctness criteria. Very few intercessions can be made while maintaining soundness, since soundness expects the debugger to observe the same semantics as the program. A clear example are debuggers that allow the user to update the code during the debugging session. We can illustrate this in the λ^{\rightarrow} by allowing the debugger to substitute terms at runtime.

The substitution debug command is similar to substitutions for let bindings in λ^{\rightarrow} (Pierce, 2002).

Figure 2-6 shows our intercession debugger semantics, as again an extension on the previous debugger semantics—shown in Figure 2-5. We add a new debug command $\text{subst } t_1 t_2$ to the debugger, which allows the user to substitute the current term t_1 with a new term t_2 of the same type.

2.6.1 Intercession breaks straightforward correctness

Unfortunately, the intercession debugger is not sound by the definition of the previous debuggers. The previous soundness criteria are defined in terms of the entire debugging sessions, starting from the beginning of the program.

This criterion can never be satisfied for all debugging session of an intercession debugger that can arbitrarily update the program code. We can illustrate this by the following example (Example 2-1), where we use the *substitution* command to change the program at runtime.

Example 2-1. The following shows a sequence of steps in the intercession debugger. Intercession commands are shown in bold.

$$\begin{array}{c}
 (\lambda x : \text{Nat} . \text{isZero } x) (\lambda y : \text{Nat} . \text{succ } y) 0 : \text{Bool} \\
 \text{AppAbs} \quad \hline \\
 (\lambda x : \text{Nat} . \text{isZero } x) ([y \mapsto 0] (\text{succ } y)) : \text{Bool} \\
 \text{Subst} \quad \hline \\
 [\text{succ } 0 \mapsto 0] (\lambda x : \text{Nat} . \text{isZero } x) \text{ succ } 0 : \text{Bool} \\
 \text{AppAbs} \quad \hline \\
 [x \mapsto 0] \text{ isZero } x : \text{Bool} \\
 \text{isZero} \quad \hline \\
 \text{true} : \text{Bool}
 \end{array}$$

In Example 2-1, the debugger changes all occurrences of *succ 0* in the program to simply 0 in the middle of the debugging session. Through this intervention, the program results in true, while the original code can clearly only be false. To our correctness criteria, this means we designed an unsound debugger. However, there are many reasons for designing a debugger that can update the program during a debugging session, allowing developers to patch code as they debug it. Moreover, there is nothing in the function of the debugger that would lead us to believe—on the face of it—that the debugger is incorrect. After all, the new program is still well typed, and the debugger observes the correct behaviour of the updated program. Therefore the problem is not that our debugger is incorrect, but it is no longer sound.

Unlike soundness, debugger completeness is not broken because of intercession. After all, there is no reason that any intercession commands should take place during the debugging session we construct in the proof. Therefore—analogous to the previous extensions to the semantics—the addition of the *Subst* rule makes no difference, and the same proof for completeness holds.

2.7 Discussion: general debugger correctness

Given the wide variety of debuggers and the vagueness around what constitutes a debugger, it is not possible to formally define a general correctness criterion that is the same for all types of debuggers. However, the *soundness* and *completeness* criteria presented in this chapter do present the same general principle, which is that the debugger should observe the same semantics as the program being debugged. This does not mean that no case can be

made for the usefulness of unsound debuggers, however, their unsoundness is important to keep in mind as a user of such debuggers.

The extensive discussion of the different debugger semantics for the λ^\rightarrow in this chapter serves to show the general applicability of debugger soundness and completeness, and support our claim that these are the most essential correctness properties for any type of debugger. The same criteria will be used throughout this dissertation, as we explore how to develop sound out-of-place and multiverse debugging techniques for constrained environments. These debuggers bridge a wide spectrum of debugger types, and intercede in the program's execution in intricate ways. They present semantics that are much more complex than the simple semantics we presented in this chapter. This will illustrate further that the correctness criteria presented in this chapter are indeed useful properties for any type of debugger.

Furthermore, the spirit of the debugger semantics in this chapter closely aligns to the design of the debuggers we will present. For instance, our multiverse debugger presented in Chapter 5 contains similar semantics to our reversible debugger for exploring the possible execution paths of non-deterministic programs. The rest of this dissertation will also mirror the structure of this chapter, by first presenting a remote debugger for WebAssembly on microcontrollers, and then extending it with more advanced features in the following chapters.

Chapter 3

A Remote Debugger for WebAssembly

*Those who abjure debugging can only do so by others
debugging on their behalf.*

— adapted from George Orwell

Developing and investigating novel debugging techniques for microcontrollers within our new formal framework, requires an easy way to instrument the program execution, and ideally prototype new debuggers quickly. The best way to achieve this is unarguably, to use a virtual machine that can run on the microcontrollers. Luckily, earlier work at Ghent University, developed just such a virtual machine, called WARDuino—which was the first-ever WebAssembly virtual machine for microcontrollers (Gurdeep Singh and Scholliers, 2019).

However, the original work was limited to a proof of concept, and many of the promises of the new WebAssembly-based approach to programming microcontrollers were not fully realised—such as, programming in high-level languages, highly portable code, the ability to easily handle asynchronous events, and by extension support for asynchronous I/O primitives. In this chapter, we present a more complete version of WARDuino, developed as part of this dissertation. We will discuss the full range of features and benefits of the new approach to programming microcontrollers proposed by WARDuino.

Three features of WARDuino, and in particular their formalisation, will be crucial for developing our advanced out-of-place and multiverse debugging techniques, in the later chapters of this dissertation. These are the (1) the *remote debugger*, (2) atomic *actions* for I/O operations, and the (3) *asynchronous event-driven callback system* in the virtual machine.

However, we will start at the beginning. Why is debugging seen as such a frustrating task in the embedded world? How can virtual machines help with this? And what are the broader challenges in embedded development that a WebAssembly-based virtual machine for microcontrollers can help overcome?

3.1 Challenges of Programming Microcontrollers

Recent advances in microcontroller technology have enabled everyday objects (things) to be connected through the internet. Smart lamps, smart scales, smart ovens and refrigerators have all become commodity devices which are connected through the internet, making up the Internet of Things (IoT). This is largely thanks to microcontrollers—small and energy efficient computers—becoming very cheap. However, the drawbacks of microcontrollers are their limited processing power and memory size. Furthermore, microcontrollers typically do not run a full-fledged operating system (VanSickle, 2001), but instead run statically compiled firmware, or a tiny real-time operating system (RTOS) (De Sio et al., 2023, Hambarde et al., 2014, Tan and Anh, 2009) specialized for microcontrollers. Due to these differences and the resource constraints of the underlying hardware, developing software for microcontrollers differs significantly from conventional computer programming, where these severe constraints do not exist to the same degree. The WARDUino virtual machine seeks to close this gap, and focus on the following six major challenges unique to IoT development.

Low-level coding. First, embedded software are usually written in low-level programming languages, such as C (Aspencore, 2023, Kernighan and Ritchie, 1989). Although C is very efficient, developing programs in C is error-prone and time-intensive. Crucially, C requires developers to manually manage memory allocations which has been shown to be notoriously difficult for complex programs (English et al., 2019, van der Veen et al., 2012).

Portability. Second, many of the functionalities of a microcontroller are memory mapped, these mappings are highly specific for each microcontroller and can differ even between devices of the same microcontroller family. Completely different microcontrollers vary even more in the way they initialize and control peripherals. Therefore, porting programs from one platform to another can be difficult and time-consuming.

Slow development cycle. Third, uploading programs to a microcontroller is a slow and tedious process. For every change in the program, however small, the entire program must be recompiled and flashed (uploaded) to the device. This slows down the development cycle as developers need to wait for this process to finish before they can test their programs.

Debuggability. Fourth, debugging facilities are often not available for microcontrollers without (expensive) hardware debuggers. Even then, the debuggers usually only work for the C language. The lack of debugging facilities makes that developers cannot easily inspect the internal state of a microcontroller. They can only observe its external behavior, for

example, that an LED that should be blinking, instead remains off. When the device is not behaving as expected, it is difficult to find the root cause of the problem. Many developers resort to printing values to the serial bus to figure out what the device is doing when something goes wrong (Makhshari and Mesbah, 2021), but this is very slow and inconvenient.

Hardware limitations. Fifth, the embedded devices powering IoT applications have severe hardware limitations compared to conventional computer systems. The most important and universal constraints for these devices, are their limited processing power and memory size.

Bare-metal execution environments. Finally, due to their heavy constraints, microcontrollers rarely run full-fledged operating systems. Instead, software is run on top of a tiny RTOS, or simply as statically compiled firmware.

3.2 Programming Microcontrollers with High-level Languages

Many of the difficulties in programming microcontrollers disappear when using higher-level languages. The abstractions in these languages can prevent whole classes of bugs and can ease development. Specifically, high-level languages relieve the programmer from manual memory management, and can provide stronger type systems to further avoid mistakes. They also make it easier to support advanced features such as over-the-air updates—where software is updated without flashing via a physical connection—and remote debugging, where a device is debugged through instructions sent from another remote device.

Some high-level languages have been ported to embedded devices using small custom virtual machines (nanoFramework Contributors, 2021, Williams, 2014, Zerynth s.r.l., 2021). Unfortunately, these virtual machines only support a subset of the language's features and only work on a specific range of hardware platforms. A popular example is MicroPython (George, 2021), which is a subset of Python for microcontrollers. For performance reasons access to the peripherals is often baked into high-level programming language. In MicroPython support for displays and sensors is baked into the language and implemented directly in C. As such, if a specific peripheral device is not supported, the language is of limited use. Another issue, is the lack of debuggers for these languages. This is also the case for MicroPython, which has no official debugger, and third party alternatives are very limited. The Mu debugger for example, supports only classic breakpoints and step instructions, and works exclusively on Raspberry Pi devices, which are much more

powerful than embedded devices under consideration in this chapter. Finally, many high-level languages do not directly support embedded devices at all, as we will discuss further in Section 3.11.

3.3 WARDuino: WebAssembly for Microcontrollers

In this work we take a different approach aimed at enabling multiple high-level languages on microcontrollers while mitigating their downsides. To accomplish this goal, we created WARDuino (Gurdeep Singh and Scholliers, 2019), a virtual machine (VM) designed to run WebAssembly (Haas et al., 2017) on microcontrollers. Since WebAssembly is a universal compile-target, it can enable programs written in a wide variety of languages to run on low-end embedded devices. This is an important design choice to improve the *portability* of our solution. The design of WebAssembly further focuses on a compact representation, since the byte code is intended to be streamable and efficient (Haas et al., 2017). This compactness is especially important when executing programs within the *hardware limitations* of the embedded devices. Additionally, WebAssembly can achieve performance speeds close to native code (Haas et al., 2017, Jangda et al., 2019), potentially outperforming other interpreters for high-level languages on microcontrollers.

The WARDuino virtual machine was first presented in 2019 by Gurdeep Singh and Scholliers (2019), and addressed *the slow development cycle* and the challenging *debuggability* through the initial implementation of a remote debugger with over-the-air reprogramming capabilities. The paper presented these two features as extensions to the operational semantics of WebAssembly, in order to show their interaction and compatibility with the WebAssembly standard, and to ease re-implementation in other virtual machines. Additionally, WARDuino provided support for a limited set of hardware features through WebAssembly functions embedded in the virtual machine. It is necessary to embed this support in the virtual machine, since the *bare-metal execution environments* of embedded devices provide no conventional interfaces to the hardware. Simultaneously, the primitives should be exposed at the level of WebAssembly in order to achieve the highest *portability* possible. However, the paper left some important problems as future work.

First, WebAssembly does not natively support asynchronous code, but many standard machine-to-machine (M2M) protocols for IoT applications such as MQTT (Banks and Gupta, 2014) rely on asynchronous events. Similarly, IoT applications often rely on asynchronous handling of hardware interrupts. Due to this limitation in WebAssembly, WARDuino lacked any support for either hardware primitives that rely on asynchronicity, or M2M protocols. In

WARDuino
supports the
first release of
WebAssembly
(MVP).

this chapter, we extend the WebAssembly operational semantics with support for event-driven callback handling. Through this system, callback functions can subscribe to asynchronous events at the WebAssembly level. The functions will be executed whenever such an event occurs. While other proposals for asynchronous code in WebAssembly are being developed (WebAssembly Community Group, 2022), these proposals are still in early stages, and often focus heavily on browser applications, making them unsuitable for resource-constrained microcontrollers.

Second, since hardware support is exposed at the WebAssembly level there is a language barrier that has to be bridged for every higher-level language. The original version of WARDuino did not address this issue, and in practice lacked any real support for high-level languages. In this chapter, we show that WARDuino can practically solve the *low-level coding* challenge as promised in the original paper (Gurdeep Singh and Scholliers, 2019). We illustrate how WARDuino can support high-level languages through language symbiosis, by showing different levels of language integration for AssemblyScript, a TypeScript-like language. These examples serve as a general recipe for implementing other language libraries.

Third, the formal rules for the debugger semantics were not used to prove any interesting properties or guarantees for the debugger. In this chapter, we improve the semantics for the debugging and over-the-air updates, and provide a proof for observational equivalence between the debugger semantics, and the underlying WebAssembly semantics. This equivalence means that the executions observed by the debugger semantics are precisely the same as those observed by the underlying language semantics.

Fourth, the virtual machine was never used to implement a real-world IoT application, and its evaluation was limited to a comparison of execution speed with only one alternative approach. In this chapter, the evaluation of WARDuino has been expanded to include a comparison to another WebAssembly runtime that can run on microcontrollers. We also present a real-world IoT application written in AssemblyScript and developed using WARDuino.

To further illustrate how WARDuino can provide an improved development experience, closer to conventional programming, we present how WebAssembly enables fast prototyping of emulators, and the improved tool support with the visual debugger plugin for WARDuino in the VS Code IDE. This plugin is an important contribution towards the increased *debugability* of IoT software in WARDuino. The chapter also includes additional code examples that explain how hardware peripherals can be accessed from WebAssembly, as well as a notably improved and expanded presentation of the WARDuino virtual machine architecture.

In summary, our novel contributions compared to the initial paper (Gurdeep Singh and Scholliers, 2019) are:

- A detailed and expanded presentation of the *improved WARDuino VM*: A WebAssembly virtual machine for embedded devices. (Section 3.5)
- *Support for IoT primitives* (asynchronous hardware peripherals and common M2M protocols) at the WebAssembly level. (Section 3.7 and Appendix D)
- A general recipe for supporting WebAssembly-level primitives in high-level languages in the form of *language symbiosis* implemented for the AssemblyScript language, presented through multiple code examples. (Section 3.6)
- The first formally described *event-driven callback system* and implementation for handling asynchronous code in WebAssembly. (Section 3.8)
- The first proof of *observational equivalence* between a debugger semantics and the WebAssembly operational semantics. (Section 3.8.3)
- An improved development experience thanks to better tool support through a *visual debugging environment* in VS Code, which currently supports debugging of WebAssembly and AssemblyScript code—and the possibility for fast prototyping of emulators thanks to WebAssembly. (Section 3.9)
- A smart light application written in AssemblyScript showcasing the new IoT primitives in WARDuino, and demonstrating that the callback system can handle both interrupts from the embedded device itself and from the network via asynchronous communication protocols such as MQTT. (Section 3.10.1)
- An expanded comparison of the execution speed of the virtual machine with another WebAssembly runtime that can run on low-end embedded devices. (Section 3.10.2)

The rest of the chapter is organized as follows. First, we show an example program and illustrate how WebAssembly code can access hardware peripherals in Section 3.4. In Section 3.5 we discuss the overall design of WARDuino. The section goes into further detail on the execution of WebAssembly programs, and the handling of interrupts within the virtual machine. Then we show how we bridge the language barrier with WebAssembly in Section 3.6. Section 3.7 briefly discusses how developers can extend the WARDuino machine themselves to support new or custom hardware peripherals. A formal description of our extensions is given in Section 3.8. In Section 3.9 we give a detailed overview of the available tools for debugging WARDuino applica-

The latest version of the VM is freely available under the Mozilla Public License 2.0

tions. We follow this discussion with the evaluation of our implementation in Section 3.10. Finally, we present related works in Section 3.11 and conclude in Section 3.12.

3.4 WARDuino: WebAssembly Programming in Practice

WARDuino is a virtual machine for the 2019 core WebAssembly standard (Rossberg, 2019). The standard does not provide instructions to interact with the environment, for example controlling the pins of a microcontroller. Neither does the *bare-metal execution environment* of embedded devices provide useful abstractions and interfaces to interact with the hardware, in the way a full-fledged operating system might. To address this shortcoming, WARDuino provides a set of primitives to interact with the environment as importable WebAssembly functions.

However, the end goal of WARDuino is not to develop IoT applications in WebAssembly, instead it is meant to enable IoT developers to use high-level programming languages. Many high-level languages can already be compiled to WebAssembly, and we can lift the WARDuino primitives to those programming languages. This means that developers can use the WARDuino primitives as normal functions in their high-level language of choice. We start with a small example to make this general idea more concrete.

3.4.1 Developing IoT programs

Programs in over 40 languages can be compiled to WebAssembly bytecode, and many popular languages provide additional support such as interacting with WebAssembly directly. Developers can use these languages to write programs for WARDuino. We will use the AssemblyScript (The AssemblyScript Project, 2023) programming language as an example in this section. AssemblyScript is a language specifically designed for WebAssembly. The main purpose of AssemblyScript is to allow web developers to use WebAssembly without needing to learn a new language. This is why the language is based on TypeScript, and many TypeScript programs are indeed valid AssemblyScript programs. AssemblyScript's main purpose strongly aligns with our goal of letting developers program embedded systems in the languages they already know and prefer. Furthermore, by being a standalone language AssemblyScript can better prioritize small code size and fast code execution, which are both very important for embedded software.

There is no official list of languages that compile to WebAssembly, but the community maintains a nearly complete list.

Listing 3-1 contains a minimal example of an MQTT program written in AssemblyScript. MQTT (Banks and Gupta, 2014) is one of the most used M2M protocols (Mishra and Kertesz, 2020) for communication in IoT applications.

```
1 import {delay, MQTT, print, WiFi} from "as-warduino";
2
3 function until(attempt: () => void, done: () => boolean): void {
4     while (!done()) {
5         delay(1000);
6         attempt();
7     }
8 }
9
10 export function main(): void {
11     until(() => { WiFi.connect("ssid", "password"); }, WiFi.connected );
12
13     let message = "Connected to wifi network with ip: ";
14     print(message.concat(WiFi.localip()));
15     MQTT.init("broker.example.com", 1883);
16     MQTT.subscribe("helloworld", (topic, payload) => { print(payload); });
17
18     while (true) {
19         until(() => { MQTT.connect("clientid"); }, MQTT.connected);
20         MQTT.poll();
21         delay(1000);
22     }
23 }
```

Listing 3-1. MQTT AssemblyScript program for WARDuino.

It allows devices to communicate with a large network of other devices via a server, designated as the MQTT broker. The broker accepts topic-based messages from clients and passes these messages on to all clients that have subscribed to these topics. WARDuino provides an MQTT module with all the necessary primitives for the microcontroller to function as an MQTT client.

The code in Listing 3-1 starts by importing all necessary WARDuino primitives from the `as-warduino` package for AssemblyScript on [Line 1](#). The `print` function is WARDuino's primitive for printing to the serial bus. The `MQTT` and `WiFi` namespaces expose the functions for communicating via the MQTT protocol and connecting to Wi-Fi networks. On [Line 3](#), we define a helper function `until()` that takes two functions as arguments: `connect` and `connected`. When `until` is called, the `connect` function is executed every second until the `connected` function returns true. We use this function in our program to establish a connection to the Wi-Fi network and the MQTT broker.

The entry point to our program is the `main` function ([Line 10](#)). It starts by connecting to the local Wi-Fi network with the help of `until()` and two WARDuino primitives: the `WiFi.connect` function that initiates a connection to a network, and the `WiFi.connected` that returns whether the micro-

controller is connected to a Wi-Fi network. Once connected, [Line 14](#) prints the microcontrollers IP address to the serial port. Again, two WARDuino primitives are used: `WiFi.localip` and `print`. The code then configures the URL and port of the MQTT broker ([Line 15](#)), and subsequently subscribes to the *helloworld* topic ([Line 16](#)). Alongside a topic string, the `MQTT.subscribe` primitive requires a callback function as second argument. WARDuino invokes this callback function for every incoming MQTT message with the set topic.

Now the microcontroller is ready to receive messages from the MQTT broker. A while loop ([Line 18](#)) checks if there are messages. To ensure the client remains connected to the server, [Line 19](#) periodically checks if it is still connected, and otherwise attempts to reconnect. After verifying the connection, we call the `MQTT.poll` function to signal WARDuino to check for new messages.

Our example highlights the goal of the WARDuino project: programming microcontrollers from many high-level language. The code illustrates how developers can use all the features of their high-level language, even those WebAssembly itself does not fully support, such as strings and anonymous functions. Using the WARDuino primitives in high-level languages, does require some glue code behind the scenes. The exact details are discussed in Section 3.6.

Underneath the high-level language library, the primitives are implemented in the WARDuino virtual machine as WebAssembly modules. The WebAssembly standard includes the use of custom WebAssembly modules, which can be used to expose functions designed to interact with the environment. In web browsers such custom modules provide interoperability with JavaScript. WARDuino uses the same mechanism to provide access to its primitives: the hardware functionalities of the microcontroller.

The implementation of the primitives is backed by Arduino libraries. Arduino (Banzi, 2008) is an open-source electronics platform that supports a wide range of microcontrollers. By providing a thin layer on top of C++, Arduino increases the portability of programs on microcontrollers. The Arduino platform does an excellent job of defining uniform libraries. For example, the code implementing the iconic blinking LED program is identical for all supported devices. This is made possible by the fact that these microcontroller boards implement a core set of libraries to access and address the input-output pins. The constant `LED_PIN` is one of those provided addresses, it holds the pin number of an LED on the board. By building on top of the Arduino libraries, we can bring the same kind of interoperability to programs compiled to WebAssembly.

Our “built-in” modules provide the most important Arduino features for controlling peripheral devices. These include GPIO, SPI, USART and PWM as well as more advanced networking modules. Specifically, we have modules with primitives to connect to Wi-Fi networks and to use the HTTP and MQTT protocols. Currently, all our modules are exposed in one single custom WebAssembly module named “env”. This is in line with the WebAssembly System Interface (WASI) specification (Hickey et al., 2020). An overview of these primitives and their WebAssembly interface can be found in Appendix D.

3.4.2 Conclusion

In this section we have shown a basic IoT program written in AssemblyScript running on top of our WARDuino VM. Our goal is to enable IoT developers to program microcontrollers in high-level languages. To facilitate this WARDuino allows developers to run WebAssembly on microcontrollers. The idea is that programs in high-level languages are compiled to WebAssembly, and executed by WARDuino. Unfortunately WebAssembly did not yet support interacting with the hardware of the microcontroller. To resolve this we provide GPIO, SPI, USART and PWM modules. Network related features are another lacuna of WebAssembly we filled with the WiFi, HTTP, and MQTT modules. Thanks to our modules, WebAssembly becomes a viable platform to program microcontrollers with WARDuino. In the next section we will take a closer look at the architecture of WARDuino.

3.5 WARDuino: Virtual Machine Architecture

The WARDuino virtual machine is at heart a byte-code interpreter for WebAssembly, around which several components have been built to improve the development cycle of IoT software. WebAssembly is the compile-target because it tackles both the challenges of *portability* and *low-level coding*. However, for WebAssembly to be a viable platform, we need a way to interact with the environment, i.e. control hardware peripherals, communicate over the internet, and so on. To address this WARDuino includes a set of primitives. Responsive IoT applications require these primitives to handle asynchronous events, standard WebAssembly does not support this. WARDuino is therefore extended with a callback handler to process asynchronous events, and pass them to user-defined callback functions. To tackle the challenge of *debuggability*, WARDuino includes a remote debugger with support for over-the-air updates. Combined with standard debugging operations, the over-the-air updates allow developers to iterate quickly and test fixes while debugging. This way, WARDuino aims to significantly improve on the *slow*

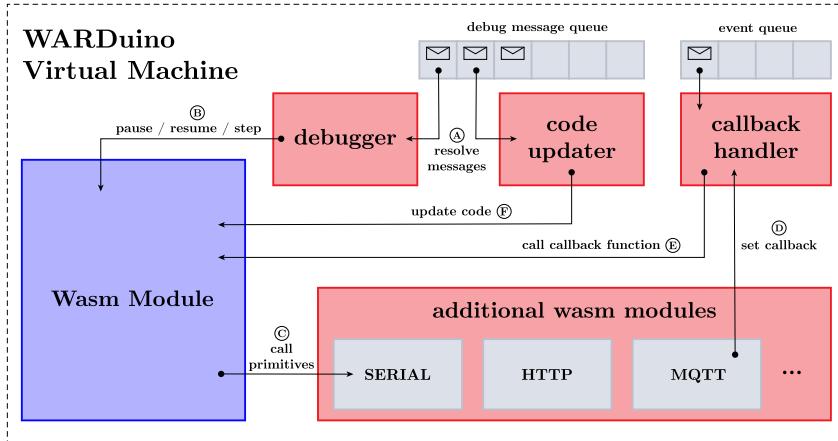


Figure 3-1. This diagram shows the architecture of the WARDuino virtual machine. The different components of the virtual machine are shown in red; the debugger, live code updater, callback handler, and additional WebAssembly modules. External devices can send debug messages to the virtual machine, for both the debugger and live code updater. They are parsed concurrently to the interpretation loop, and placed into the message queue. Asynchronous events for the callback handler are processed analogously, and placed into the event queue. Both queues are shown in gray to indicate that they are populated by platform specific code, outside the interpretation loop. The program (WebAssembly module) executed by the virtual machine is shown in blue. The arrows indicate the interactions between components, which are executed in the interpretation loop.

development cycle of embedded software. In this section, we give an overview of the virtual machine architecture, and show how the components interact with the interpretation of the loaded program, as well as each other.

3.5.1 WARDuino Components

Figure 3-1 gives a high-level overview of the virtual machine's architecture, highlighting how the novel components (shown in red) relate to each other and interact with the running program (shown in blue). This program is a WebAssembly module, which will usually be compiled from a high-level language.

WARDuino allows developers to debug and update the running program over the air. The virtual machine can receive update and debug messages over different channels, such as Wi-Fi or the serial port. Whenever a message arrives, it is put in the debug message queue, where it is visible to the main

interpretation loop. During interpretation, the virtual machine will periodically check the queue for new messages and resolve them one at a time as shown in Figure 3-1 (A). Debug messages can instruct the VM to pause, step or resume execution (B). Update messages can replace the entire WebAssembly module, single functions, or even single variable values (F).

Importantly, WARDuino contains a number of WebAssembly modules, implementing common libraries and functionality for microcontrollers, such as the `Serial` module or the `HTTP` module (C). WebAssembly programs can use the primitives from these modules in order to access the hardware of the microcontrollers. Due to the primitives being defined at the level of WebAssembly, it is not always straightforward for developers to use the primitives in their high-level source language. Language specific libraries can enhance the interoperability between a source language and the low-level interfaces of the WebAssembly primitives. Section 3.6 goes into further detail on supporting high-level languages through language specific libraries.

Microcontrollers often receive signals from peripherals through hardware interrupts. These are then typically processed by asynchronous interrupt handlers. This way, the embedded device does not have to block execution by actively waiting for input. Unfortunately, calling a function asynchronously is not supported by standard WebAssembly. In other words, a standard WebAssembly virtual machine cannot call a function to handle asynchronous events such as MQTT messages, hardware interrupts, and so on. To address this shortcoming, we have implemented a novel callback handling system for executing WebAssembly functions when certain events happen. WARDuino programs can use this callback handling system to handle asynchronous events. The MQTT module, for instance, can be used to register a WebAssembly function from the loaded program as a callback for specific events (D). Whenever these events occur, our callback handler will invoke the registered function and pass all relevant information to it (E). In the rest of our chapter, we will refer to these functions as callback functions or simply callbacks.

In Appendix D.7 the `MQTT subscribe` primitive illustrates how primitives can receive the table index of callback functions as arguments.

3.5.2 WARDuino Interpretation

WebAssembly is a stack-based language, defined over an implicit operand stack. This means WebAssembly runtimes do not have to explicitly use this stack. In WARDuino, however, we implement the VM as a stack-based virtual machine based on the open source `wac` C-project by Joel Martin¹. Our WebAssembly operand stack is implemented as two separate stacks: the main

¹<https://github.com/kanaka/wac>

operand stack, and a call stack. The call stack keeps track of the active functions and blocks of the program and where the execution should continue once they complete. When initializing the module, we seed the call stack with a call to the main entry point of the program. The main operand stack holds a list of numeric values from which WebAssembly operations pop their arguments, and to which they push their results. This stack starts out empty.

Algorithm 3-1 shows the main interpretation loop of WARDuino as pseudocode. WARDuino executes a WebAssembly module m , instruction by instruction, in a single loop (Line 3). Before any instruction is interpreted, the *resolveDebugMessage* function checks the debug message queue for new incoming messages (Line 4), resolves the oldest one, and possibly pauses the runtime. If the runtime is not paused, the virtual machine checks the event queue for new asynchronous events, and possibly resolves at most one before starting the actual interpretation. If the runtime is paused however, the virtual machine will go to sleep until a new message arrives in the queue (Line 6). The *awaitDebugMessage* function does not resolve debug messages, instead the code jumps back to the start of the loop and the debug message is resolved by the *resolveDebugMessage* function. We discuss the debug message and event resolution in more detail in, respectively Section 3.5.3 and Section 3.5.5.

```

1 Require module  $m$  and execution state  $s$ 
2 done  $\leftarrow$  false, success  $\leftarrow$  true
3 while !done and success do
4   | resolveDebugMessage( $s$ ) ▶ Can update the execution state  $s$ 
5   | if  $s$  = paused then
6     |   | awaitDebugMessage() ▶ Wait until debug queue is not empty
7     |   | continue ▶ Go back to the start of the loop
8   | resolveEvent() ▶ Run callback for event, if any in the queue
9   | opcode  $\leftarrow$  getOpcode( $m$ )
10  | switch opcode do
11    |   ...
12    |   | case 0x7c ... 0x8a
13    |   |   | success  $\leftarrow$  interpretBinaryi64( $m$ , opcode) ▶ Perform i64 binary operation
14    |   |   ...
15    |   | m.pc  $\leftarrow$  m.pc +1 ▶ Increment program counter
16  | if not success then
17  |   | throw trap ▶ Check if any operation threw a trap

```

Algorithm 3-1. Main loop for interpretation in the WARDuino virtual machine.

For interpreting instructions, the virtual machine keeps track of its own program pointer $m.pc$, which points to the next instruction to be executed in the program buffer. We may dereference this pointer to get the next opcode to execute (Line 9), for example $0x7f$. A switch statement then matches the current opcode (Line 10). For our example, the switch determines our opcode to be a binary operator for 64-bit integers that will be handled by the *interpretBinaryi64* function. This function resolves the instruction further and returns whether it succeeded. If so, the while-loop continues, and the next opcode is processed. Otherwise, success will become false, and the while loop will stop interpretation.

We refer interested readers to the paper by Haas et al. (2017) for more information on traps in WebAssembly.

When the interpretation loop stops due to a failure, the virtual machine will throw the underlying trap (Line 17). Alternatively, interpretation halts whenever the end instruction ($0x0b$) of the main entry point is reached. In this case, the *done* variable will be set to `true`, and the main interpretation loop will stop successfully without throwing a trap.

In Algorithm 3-2 we show the most relevant parts of *interpretBinaryi64*. The function is used to interpret all binary operators defined by WebAssembly on 64-bit integers. First, it gets the two arguments for the binary operation from the operand stack (Line 2). Next, the function matches the opcode with a specific operation, in our case the `i64.div_s` operation. If the arguments are valid for the operation, the division is executed (Line 10), the result is placed on the top of the stack (Line 12), and the function returns `true` indicating success (Line 13). When the function encounters an illegal operation such as a division by zero, it returns `false` instead (Line 8). In that case, the main loop of the virtual machine will stop interpretation of the program and throw an exception, as shown on Line 17 in Algorithm 3-1. Most of the code for interpreting the WebAssembly operations is structured analogously to the function highlighted in Algorithm 3-2.

3.5.3 Resolving Debug Messages

Debug messages for WARDuino are received and parsed concurrently from the main interpretation loop, by device and communication channel specific code. Messages are placed on a FIFO queue. The interpretation loop will check this queue at the start of each iteration (Algorithm 3-1, Line 4). When the queue is not empty, exactly one message is processed. This means the execution state of the virtual machine can change, for instance from running to paused. If the program should be paused, the virtual machine will wait until the debug messages queue is not empty (Algorithm 3-1, Line 6), before continuing at the start of the interpretation loop.

```
1 function interpretBinaryi64(m, opcode)
2   | d, e  $\leftarrow$  popStack(m, 2)
3   | f  $\leftarrow$  0
4   | switch opcode do
5   |   ...
6   |   | case 0x7f
7   |   |   | if e = 0 then
8   |   |   |     | throw "division by zero"
9   |   |   |     | return false
10  |   |   |     | f  $\leftarrow$  d  $\div$  e
11  |   |   ...
12  |   | pushToStack(m, f)
13  | return true
```

Algorithm 3-2. Function to interpret operators for 64-bit integers.

3.5.4 Calling primitives

WARDuino primitives are exposed to the running program as imported WebAssembly functions. In fact, all imported functions must be primitives defined in the virtual machine, since the current version allows only one user-defined WebAssembly module to be loaded at a time. The WARDuino primitives are exposed through one single “env” module. This is in line with the WebAssembly System Interface (WASI) specification (Hickey et al., 2020). As stated before, the env module is implemented in the VM.

When an opcode specifies that a WebAssembly function must be called, some extra work is needed. First, the current instruction and stack pointers are stored in a frame and pushed to the call stack. The program pointer $m.pc$ is replaced by the first instruction of the function to be called. In the next iteration of the while loop (Algorithm 3-1, Line 3), the virtual machine will execute the function’s instructions. When the end instruction (0x0b) is encountered, the function has finished. The execution must now continue from the point where the call was originally made. To jump back to this place we pop the last frame from the call stack. This frame contains the program counter where we ought to continue execution. We reset our program and stack pointer to the appropriate values and continue executing. If the function returned a value, it will reside on the top of the main operand stack.

WARDuino programs can be developed in multiple high-level languages thanks to WebAssembly. Currently, the WARDuino project includes example programs written in Rust, AssemblyScript, and C. We go into further detail on the support for high-level languages in Section 3.6.

Rust and AssemblyScript programs can be found under the tutorials folder in the [GitHub repository](#), and the benchmarks folder includes C programs.

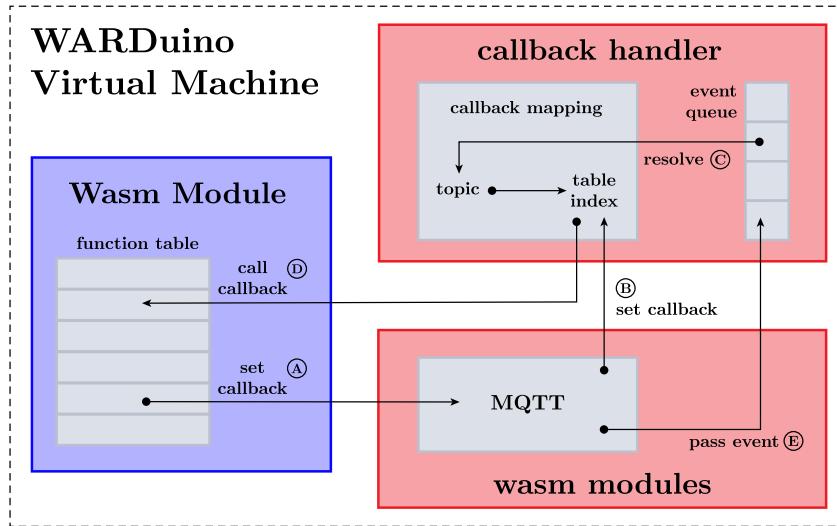


Figure 3-2. This diagram shows how callbacks are resolved in the virtual machine. The event queue is populated with events concurrently to the interpretation loop, any time the microcontroller receives a hardware interrupt.

The primitive operations (i.e. `digital_write`) are implemented in the WARDUINO virtual machine in native C code. This implementation depends on the target microcontroller platform. Currently, WARDUINO focuses on the Arduino platform which can be used with many families of embedded devices, such as ESP32's, Arduino boards, and some Raspberry Pi devices. To illustrate the portability of WARDUINO, the virtual machine includes partial support for ESP IDF. The WebAssembly interface of the primitives is the same for both implementations, to provide the best portability for WARDUINO programs. To make these interfaces compatible with the VM the primitives conform to the standard WebAssembly calling conventions, i.e. they read their arguments from the stack and place their return value on the stack.

The current status of supported platforms can be found on the [documentation website](#).

3.5.5 Callback Handling

The WARDUINO callback handling system is used to call WebAssembly functions when specific real-world events occur. These events can range from interrupts caused by a local button press to MQTT messages arriving over Wi-Fi. Similar to debug messages, asynchronous events are received and placed into a queue concurrently to the main interpretation loop. As shown in Algorithm 3-1, the main interpretation loop will resolve a single event—if any is present—immediately after checking for incoming debug messages.

Before events can be resolved, callback functions must be registered for the topics of the events the program expects to receive. Figure 3-2 gives a schematic overview of the callback handling system in the WARDuino virtual machine. When developing our callback handling system, the two most important concerns are: (a) to keep the system lightweight, and (b) to offer the flexibility required to support the wide range of asynchronous protocols and libraries that already exist for microcontrollers. Precisely for these concerns, we developed a reactive event-driven system.

Callback handling in WARDuino works as follows. Within WebAssembly, functions can be stored into a table, enabling them to be referenced by their table indices. WARDuino uses this same mechanism for the callback functions. For instance, consider an MQTT `subscribe` primitive that subscribes to an MQTT topic with a given callback function (more information can be found in Appendix D.7). In the WebAssembly program we pass the table index of the callback function to the `subscribe` primitive, as shown in Figure 3-2 . The WARDuino MQTT library then uses this index to register a callback with the global callback handler in the WARDuino virtual machine. This handler holds a mapping of topic strings to table indices. Each topic string can be mapped to at most one callback.

We do not allow multiple callbacks for a single topic string at the level of WebAssembly instructions, but the WebAssembly primitives we built on top of this system do in fact support registering multiple callbacks. This gives the same result for developers writing programs in a high-level language in WARDuino. However, it does make a significant difference for the WebAssembly specification, as we will explain in Section 3.8.5.

Whenever the virtual machine wants to resolve an event (Algorithm 3-1, Line 8), the callback handler takes the oldest event from the queue and looks up its topic in the callback mapping . The mapping returns the table index of the registered callback function. Through this index the callback handler can set up the call for the correct WebAssembly function on the call stack, and add the topic and payload of the event as arguments to the operand stack . In other words, the callback handler does not execute the callback functions itself, it merely sets up the appropriate calls on the stacks. When the interpretation loop resumes it will automatically execute the callback function. Executing callbacks is therefore completely transparent to the virtual machine, since it is just another function call. Furthermore, the virtual machine does not need to know whether an event was actually processed by the callback handler. This does force callback functions to never return a value. However, this is a reasonable requirement that many other microcontroller platforms also impose on their interrupt callbacks (Banzi, 2008, Espressif Systems, 2023a). After all, since the callbacks are executed concurrently to interpretation and

The precise signature is shown as part of the operational semantics in Section 3.8.5.

in complete isolation, there is no way of using the return value anyway. Therefore, after the callback function is resolved, the interpretation of the program continues as if no additional function was called.

There is a possible pitfall with adding callbacks to the call stack at any point during execution. In light of the microcontroller's limited memory, it is easy for the call stack to grow too rapidly. Therefore, we prohibit that callbacks interrupt other callbacks. In practice, the virtual machine keeps track of whether a callback is being executed by adding a marker on the call stack just before the callback. When the virtual machine encounters this marker again, it knows that the callback completed. So when *resolveEvent* is called in Algorithm 3-1, and the last callback has not yet completed, the callback handler will never resolve an event.

3.5.6 Summary

The WARDuino virtual machine has all the ingredients to develop IoT applications for microcontrollers in high-level languages. We discuss the practicalities of using high-level languages in Section 3.6. The virtual machine includes primitives that give the WebAssembly programs access to the hardware peripherals and other IoT capabilities of the microcontrollers. The architecture of our virtual machine is extensible in many ways, as we discuss in Section 3.7. Through the framework discussed in Section 3.7 many Arduino libraries can be implemented in WARDuino.

Our novel callback handling system provides an event-based callback system where WebAssembly functions can be assigned to topics. Events are handled concurrently to interpretation of the WebAssembly program, and callback functions subscribed to the corresponding topic are called at well-defined points in the program execution. This way, these functions can react to hardware interrupts or other asynchronous events.

Because microcontrollers often do not have a keyboard or screen, WARDuino provides remote debugging support. This enables developers to set breakpoints and pause or step the execution remotely. Even more, WARDuino allows over-the-air updates of variables and functions as a whole. Section 3.9 contains more details on the tools available for debugging with WARDuino. In the next section we will look further into the features of the WARDuino project that aim to overcome this language barrier.

Blocked callbacks do not get lost, they are processed after the current callback completes.

A current list of already implemented libraries can be found in the official documentation of WARDuino.

```
1 export function fib(n: i32): i32 {
2     let a = 0, b = 1;
3     if (n > 0) {
4         while (--n) {
5             let t = a + b;
6             a = b;
7             b = t;
8         }
9         return b;
10    }
11    return a;
12 }
```

Listing 3-2. AssemblyScript function that calculates the n-th Fibonacci number.

3.6 Support for High-level Languages

In WARDuino hardware functionality is exposed through WebAssembly primitives. These low-level building blocks allow developers to build Internet of Things applications for microcontrollers. While our primitives are valuable in their own right, their interfaces are low-level compared to the high-level languages we want to use them from. Unfortunately, there is no generic way to create a high-level interface that is fit for every language. Languages differ in their design philosophy or may even use a different programming paradigm altogether. Furthermore, when creating interfaces, an implementer can choose to what degree they wish to offer language interoperability. In this section, we discuss how to implement high-level interfaces for WARDuino primitives, by showing different levels of interoperability for the AssemblyScript programming language. This implementation strategy is similar for all languages compiling to WebAssembly.

3.6.1 AssemblyScript as Source Language

Let us first consider AssemblyScript code that does not use WARDuino features. Listing 3-2 shows a function that calculates the n-th Fibonacci number. When we compile a basic program like this to WebAssembly, any runtime fully implementing the official WebAssembly specification should be able to run it. However, this is not the kind of program we typically want to run on microcontrollers with WARDuino. The computed Fibonacci only lives inside the microcontroller and is not visible to the outside world. To make it visible, the program needs to affect the pins of the microcontroller in some way.

```

1 import * from "as-
  warduino";
2
3 export function main(): void
{
4   let led = 16;
5   pinMode(led, OUTPUT);
6
7   let pause = 1000;
8   while (true) {
9     digitalWrite(led, HIGH);
10    delay(pause);
11    digitalWrite(led, LOW);
12    delay(pause);
13  }
14}
1  export const LOW: u32 = 0;
2  export const HIGH: u32 = 1;
3  export const OUTPUT: u32 = 0x2;
4
5 @external("env", "chip_delay")
6 export declare function delay(ms: u32): void;
7
8 @external("env", "chip_pin_mode")
9 export declare function pinMode(pin: u32,
10                               mode: u32): void;
11
12 @external("env", "chip_digital_write")
13 export declare function digitalWrite(pin: u32,
14                                     value: u32): void;

```

Listing 3-3. Blinking LED example in AssemblyScript with the necessary and minimal glue code.

3.6.2 Importing External WebAssembly Functions

Our next example (Listing 3-3) is a small program that uses WARDuino primitives in AssemblyScript. On the left side we show the code for the traditional blinking LED program. The right side contains the minimal glue code required to make the program work. The glue code imports our WARDuino primitives and defines some useful constant values.

Entities from external WebAssembly modules can be imported in AssemblyScript with an `@external` annotation. This annotation specifies both the module and primitive name to be imported. The function declaration below the annotation mirrors the imported primitives interface. On Lines 7 and 8, for example, WARDuino's `chip_delay` primitive is imported and declared to AssemblyScript as the function `delay` which has one `u32` argument and returns `void`.

Our glue code will be the same for all AssemblyScript programs. As such, we can implement it as an AssemblyScript library. By using the `export` keyword we export our declarations. This approach abstracts away the underlying WARDuino interfaces. Developers can now simply import the `as-warduino` library as shown on the first line of the blinking LED program. When they do this, they can use the WARDuino primitives as if they were normal TypeScript functions.

3.6.3 Using Interfaces with Strings

For the blinking LED example, we only used primitives with simple numeric parameters and return values. Primitives with string arguments and return values are less straightforward to port. As detailed in Appendix D.4, we represent strings as two integers: a start index in the memory and the length of the string.

Unlike WebAssembly, AssemblyScript contains types for representing and manipulating strings directly. As such it is unnatural for developers to pass strings as numeric values to functions in AssemblyScript. When AssemblyScript code is compiled to WebAssembly, the compiler translates strings into a new representation using only basic numeric types. We created a similar translation from strings to numeric types when implementing primitives with strings in our VM. Unfortunately, we have no guarantee that these two translations are the same. AssemblyScript encodes strings with UTF-16 by default, which uses two bytes to encode most characters. But as we expect to use mostly ASCII characters, and we want to keep code sizes small for microcontrollers, we prefer to use UTF-8 instead, where characters are represented primarily with only one byte.

If we use the same approach as we did for the LED example we arrive at the code in Listing 3-4. It shows a simple AssemblyScript program that uses WARDuino's HTTP POST primitive. On the right side of the figure, we give the minimal glue code that only imports the WARDuino primitive with their exact interfaces. This means that each string argument must be translated to two integers by the developer. This is not the only hurdle they must overcome. Due to the encoding inconsistencies between AssemblyScript and WARDuino, strings must be manually transformed to UTF-8. Additionally, to receive a response, WARDuino expects a memory slice as last argument where the response is stored to. The developer must allocate an ArrayBuffer for this and pass this as the last two arguments of the call.

Working with this minimal glue code requires very specific knowledge about the inner workings of WARDuino. This is not desirable. The minimal glue code does not effectively bridge the differences in abstraction levels between AssemblyScript and our WARDuino primitives. We can improve on the glue code by extending it with functions that actually use strings instead of numeric values.

The improved glue code for the HTTP primitives unburdens the developer from managing text encoding, by handling it in the AssemblyScript library. Listing 3-5 shows the new library code on the right. The code imports the WARDuino HTTP primitives under the names `_http_post` and `_http_get`. Instead of exporting these functions directly, the glue code wraps them in

```

1 import * from "as-warduino";
2 export function main(): void {
3   // ... connect to Wi-Fi ...
4   // Send HTTP request
5   let url = "https://example.com/post";
6   let body = "Bridge the Language Gap";
7   let content_type = "text/plain";
8   let response = new ArrayBuffer(100);
9   httpPOST(String.UTF8.encode(url, true),
10   String.UTF8.byteLength(url, true),
11   String.UTF8.encode(body, true),
12   String.UTF8.byteLength(body, true),
13   String.UTF8.encode(content_type, true),
14   String.UTF8.byteLength(content_type,
15   true),
16   response, response.byteLength);
17 }
18
19 export const WL_CONNECTED: u32
20 = 3;
21
22 @external("env", "http_get")
23 export declare function httpGET(
24   url: ArrayBuffer, url_len: u32,
25   buffer: ArrayBuffer,
26   buffer_size: u32): i32;
27
28 @external("env", "http_post")
29 export declare function
30 httpPOST(
31   url: ArrayBuffer,
32   url_len: u32,
33   body: ArrayBuffer,
34   body_len: u32,
35   content_type: ArrayBuffer,
36   content_type_len: u32,
37   buffer: ArrayBuffer,
38   buffer_size: u32): i32;

```

Listing 3-4. Example AssemblyScript program with HTTP GET without strings.

another function. These wrappers take care of the necessary conversions and have a more natural external interface: they use AssemblyScript strings as argument and return type. The library now exports these more natural wrappers instead of the “raw” WARDuino primitives. We can even use AssemblyScript namespaces to group the HTTP functions together, to avoid name collisions and form a logical interface. Developers can now write the much more naturally feeling code on the left of Listing 3-5, where the post function accepts strings and returns a string. The type annotations on our wrapper function provide an extra benefit: they allow the AssemblyScript type checker to validate whether the function is indeed called with strings.

3.6.4 Higher Levels of Language Interoperability

While the string version of the HTTP POST primitive is already a huge improvement over the numeric version, it still requires three string arguments. Conventionally, TypeScript-like languages use objects to send complex arguments to functions. In Listing 3-6, we show a program, and the associated glue code where the exported post function accepts an object of class Options rather than three strings. The class declaration on the first line of the right listing in Listing 3-6 defines that a value of type Options must have the keys url, body and content_type which all should be assigned to a string.

```

1 import {HTTP} from "as-
2 warduino";
3
3 export function main(): void {
4 // ... connect to Wi-Fi ...
5 // Send HTTP request
6 let response = HTTP.post(
7 "https://example.com/post",
8 "Bridge the Language Gap",
9 "text/plain");
10 }
1 @external("env", "http_get")
2 declare function _http_get(...): i32;
3
4 @external("env", "http_post")
5 declare function _http_post(...): i32;
6
7 export namespace HTTP {
8   function get(url: string,
9               buffer: ArrayBuffer): i32 {
10     return get(String.UTF8.encode(url, true),
11                String.UTF8.byteLength(url,
12                                          true),
13                buffer, buffer.byteLength);}
14
15   function post(url: string, body: string,
16                 content_type: string): string
17   {
18     let response = new ArrayBuffer(100);
19     _http_post(String.UTF8.encode(url, true),
20                String.UTF8.byteLength(url, true),
21                String.UTF8.encode(body, true),
22                String.UTF8.byteLength(body, true),
23                String.UTF8.encode(content_type, true),
24                String.UTF8.byteLength(content_type,
25                                          true),
26                response, response.byteLength);
27     return String.UTF8.decode(response,
28                               true);}
29   }
30 }
```

Listing 3-5. Example AssemblyScript program with HTTP GET with glue code for strings.

Thanks to this definition, AssemblyScript’s type system enforces that all required keys are present in the arguments to post.

3.6.5 Other Modules and Languages

Language interoperability is needed to facilitate access to WARDuino’s primitives. We implement it as a library that can be easily imported by developers. Although we only highlighted the HTTP module in this section, our AssemblyScript library contains glue code for all the WARDuino primitives discussed in Section 3.4.

Because different programming languages follow different conventions or even different programming paradigms all together, language interoperability must be dealt with separately for each language. Luckily we can follow the same approach as we did for AssemblyScript to create interoperability

```

1 import {HTTP} from "as-
warduino";
2
3 export function main(): void {
4   // ... connect to Wi-Fi ...
5
6   // Send HTTP request
7   let options: HTTP.Options = {
8     url: "https://example.com/
  post",
9     body: "Bridge the Language
  Gap",
10    content_type: "text/plain"
11  };
12  let response =
13    HTTP.post(options);
14
15 }
1
2   class Options { url: string; body: string;
3   content_type: string; }
4
5   function post(options: Options): string {
6     let response = new ArrayBuffer(100);
7     _http_post(String.UTF8.encode(options.url,
  true),
8       String.UTF8.byteLength(options.url,
  true),
9       String.UTF8.encode(options.body, true),
10      String.UTF8.byteLength(options.body,
  true),
11      String.UTF8.encode(options.content_type,
  true),
12      String.UTF8.byteLength(options.content_typ
  true),
13      response, response.byteLength);
14
15   return String.UTF8.decode(response, true);
16 }

```

Listing 3-6. Example AssemblyScript program with HTTP GET with glue code for objects.

libraries for other languages. As an example, we also created a WARDuino library for Rust, another popular programming language with WebAssembly support. Rust encodes strings as UTF-8 by default, so our library for this language does not need to change the string encoding.

Interoperability can be provided at different levels. We have seen three implementations of AssemblyScript glue code for WARDuino's HTTP module. The first version simply exported the “raw” WARDuino primitives. This meant that the developer needed to know the inner workings of WARDuino to use these functions. They needed to know how strings were represented, for example. Our second version abstracted the interface, and allows developers to use it without having to worry about WARDuino internals. By abstracting the interface we also allowed AssemblyScript to validate the types of arguments to our primitives. Finally, in a third version we adapted the glue code to adhere more closely to the informal conventions of the language. By doing so, WARDuino has similar function signatures to other libraries in the language.

3.6.6 Summary

To use high-level languages with WARDuino in practice, the primitives need to be lifted from their WebAssembly interface to the host language. In this section we showed how this interoperability can be implemented to various

degrees, ranging from using the low-level WebAssembly interface directly, to a high-level interface that integrates completely with the paradigms of the higher-level language. The examples listed here can be used as a general recipe for implementing language integration libraries in other languages that compile to WebAssembly. For instance, programs written in C, Rust, and AssemblyScript have been used with WARDuino using the implementation strategies outlined here.

Examples can be found on the [documentation website](#) and in the [GitHub repository](#)

3.7 Extending the Virtual Machine

In the previous sections we explained that WARDuino has native support for the most significant features of the microcontroller, such as GPIO->SPI, PWM, SPI, as well as communication protocols, such as HTTP and MQTT. However, we need to keep the memory constraints of the microcontrollers in mind. Given the *hardware limitations* of embedded devices, it is important to keep the WARDuino virtual machine as small as possible. We therefore restricted the supported libraries to the most essential ones for embedded applications. Furthermore, when compiling the virtual machine, developers can disable select primitives to reduce the size of WARDuino further. On the other hand, developers can add new primitives to the WARDuino VM for specific functionality or hardware they require for their projects. In this section we give an overview of how to add new primitives to the WARDuino VM.

For readers familiar with OS architectures, this is somewhat familiar to the unikernel approach.

3.7.1 Creating User-Defined Primitives

In this section, we show how we implemented the `digital_write` primitive in the WARDuino virtual machine. Developers that need a library that is not supported by our VM can use a similar approach to add it to WARDuino.

Our virtual machine keeps a table of all primitive functions. Each entry contains a name, a type specifier and an implementation. Programmers can extend this table by providing these details. The type specifier is used by the VM to validate if the primitive is called with the right arguments. If an inconsistency is detected at runtime, WARDuino throws an error. Note that this will not happen if the programmer has type-checked their code. Almost all compilers that produce WebAssembly will produce type-checked code. Our runtime checks are useful during the development of the primitives themselves.

The process for adding new primitives consists of the four steps we describe below.

```

1  typedef struct Type {      1  uint32_t
2  uint8_t form;            1  param_U32_arr_len2[2]
3  uint32_t                2  = {U32, U32};           2
4  uint32_t param_count;    3
5  uint32_t *params;        4  Type twoToNoneU32 = {
6  uint32_t result_count;   5  .form = FUNC,
7  uint32_t *results;       6  .param_count = 2,
8  uint64_t mask;          7  .params =
9 } Type;                  8  param_U32_arr_len2,
10                         9  .result_count = 0,
11                         10 .results = nullptr,
12                         11 .mask = 0x80011
13 };

```

```

1  def _prim(digital_write,
2           twoToNoneU32)
3  {
4      auto pin =
5      arg1.uint32;
6      auto val =
7      arg0.uint32;
8      digitalWrite(pin,
9                  val);
10     pop_args(2);
11     return true;
12 }

```

Listing 3-7. *Left:* The Type struct. *Middle:* A Type specifier for a primitive that takes two 32-bit unsigned integer (u32) and returns nothing. *Right:* The implementation of the digital_write primitive.

First, the programmer needs to indicate that the number of primitives has changed by increasing the NUM_PRIMITIVES constant, this variable is used to allocate the primitives table.

Second, the implementer defines the type of their custom primitive. In WARDuino the type of a function is represented by the struct shown on the left side of Listing 3-7. The form field indicates the form of the type, in the virtual machine, which is one of: function type, table type, memory type and global. For primitives this field will always be a “function type” i.e. FUNC. The following fields indicate how many arguments (param_count) and how many return values (result_count) the type has. Both counts are followed by a pointer to an array containing the specific types of the arguments/return values. Finally, each type has a mask that allows for quick comparison of types in the VM. The get_type_mask function can derive the appropriate mask for a type struct. We have predefined the most common types, these are available when defining new types. One of these predefined types is the type for a primitive taking two 32-bit integer as an argument and returning nothing, its definition is shown in the middle of Listing 3-7.

Third, after the programmer has defined the type specifier, the primitive itself can be implemented. On the right side of Listing 3-7, we show the implementation of our digital_write primitive. Primitives are defined using our def_prim macro. This macro expects two arguments, and a function body. The arguments are the name and type specifier of the primitive. The function body implements the primitive. Developers can use the macros arg0 to arg9 to access the first 10 values on the stack. The arg0 macro returns the argument that was pushed most recently onto the stack. A pop_args() macro allows popping values from the stack. The implementation may use

any library that is available at compilation time. Additionally, it may use the callback system, an example of which will be discussed in Section 3.7.2. Every primitive must return a boolean value. This value is used to indicate whether the function succeeded. If `false` is returned, the primitive has failed, and the virtual machine will throw a trap.

Finally, the implementer makes the custom function available to the rest of the virtual machine and the WebAssembly modules it executes. This only involves adding the primitive into the primitives table with the `install_primitive` macro. Once this is done, the primitive is ready to be used in WebAssembly programs for WARDuino.

3.7.2 Using Callbacks with Primitives

Our callback system enables developers to implement asynchronous libraries as modules for WARDuino. In this section we will illustrate how our callback system can be used to define asynchronous primitives. To do this, we look at the implementation of two MQTT primitives: `mqtt_init` and `mqtt_subscribe`.

The heavy lifting of our MQTT module is carried out by the `PubSubClient` Arduino library. Our primitives act as a wrapper around this library.

Listing 3-8 shows the implementation of the `mqtt_init` primitive on Lines 1 to 13. This primitive initializes the underlying `PubSubClient` library, and sets the URL and port of the MQTT broker to connect to (Line 4). The `PubSubClient` library only supports assigning one callback that will receive all the events for all subscribed topics. WARDuino's callback handling system is more flexible and allows developers to assign different callback function for each topic. During initialization of the MQTT module we use a lambda expression to set the callback of the `PubSubClient` library on Line 7. This function forwards each incoming MQTT event to WARDuino's `CallbackHandler`. The `CallbackHandler` will then in turn invoke the right WebAssembly callbacks when messages arrive.

Lines 15-27 of Listing 3-8 implement the MQTT subscribe primitive. It allows developers to register a WebAssembly function as a handler for a specific MQTT topic. After retrieving and parsing the arguments to the primitive (Lines 16-17), the function does three things. First, it creates a `Callback` object that holds a reference to the WebAssembly module, the topic, and the index of the WebAssembly callback function (Line 19). Second, this `Callback` object is added to the `CallbackHandler`. Third, in order for the subscribed messages to be passed to the `CallbackHandler` on Line 8, the function needs to tell the underlying `PubSubClient` library to subscribe to the given topic (Line 22).

```

1 def_prim(mqtt_init, threeToNoneU32) { // Initialize the Arduino MQTT Client
2     uint32_t server_param = arg2.uint32; uint32_t length = arg1.uint32;
3     uint32_t port = arg0.uint32;
4     const char *server = parse_utf8_string(m->memory.bytes, length,
5         server_param).c_str();
6     mqttClient.setServer(server, port);
7
8     // Add MQTT messages as events to callback handling system
9     mqttClient.setCallback([](const char *topic, const unsigned char *payload,
10         unsigned int length) {
11         CallbackHandler::push_event(topic, payload, length);
12     });
13     pop_args(3);
14     return true;
15 }
16 def_prim(mqtt_subscribe, threeToOneU32) { // Subscribe to a MQTT topic
17     uint32_t topic_param = arg2.uint32; uint32_t topic_length = arg1.uint32;
18     uint32_t fidx = arg0.uint32;
19     const char *topic = parse_utf8_string(m->memory.bytes, topic_length,
20         topic_param).c_str();
21
22     Callback c = Callback(m, topic, fidx);
23     CallbackHandler::add_callback(c); // Register callback function with WARDuino
24
25     bool ret = mqttClient.subscribe(topic);
26     pop_args(2);
27     pushInt32((int)ret);
28     return true;
29 }
```

Listing 3-8. Implementation of the `mqtt_init` (top) and `mqtt_subscribe` (bottom) WARDuino MQTT primitives using the event-based callback handling system.

Our new callback handling system allows WARDuino to define asynchronous primitives. These primitives can handle asynchronous foreign events such as hardware interrupts. To work with asynchronous primitives, developers simply use them in their programs to add callback functions. WARDuino will then transparently execute them in response to incoming events.

3.7.3 Summary

In this section, we showed how users can define new primitives and add them to the VM in a four-step process. Using this system users can add support for new sensors and actuators to WARDuino. When implementing primitives,

developers can use the internal callback handling system of the WARDuino virtual machine, to create asynchronous primitives.

The callback handling system is a key aspect of the virtual machine that extends standard WebAssembly. Another such aspect is the remote debugger. We discuss both components as formal extension to the WebAssembly specification in the next section.

3.8 Formal Specification of WARDuino

WebAssembly is strongly typed, and both its type system and execution are precisely defined by a small step semantic. Such a precise definition gives the WebAssembly community a universal way to propose changes and extensions to the standard.

In this section we formalize WARDuino’s architecture, by presenting it as three extensions to the WebAssembly specification. We start with a very brief summary of WebAssembly’s formal description in Section 3.8.1. This overview is followed by the small step semantics for our remote debugging (Section 3.8.2), over-the-air updates (Section 3.8.4), and callback handling features (Section 3.8.5). Each of these extensions can be defined entirely independently of the others, but here we present the over-the-air updates as an extension of the debugger semantics to highlight their compatibility. Primitives are part of the custom modules, and are therefore out of scope for the specification and will not be formalized here.

3.8.1 WebAssembly

WebAssembly is a memory-safe, compact and fast bytecode format designed to serve as a universal compilation target. The bytecode is defined as a stack-based virtual instruction set architecture, which is strictly typed to allow for fast static validation. However, its design features some major departures from other instruction sets, and resembles much more the structure of programming languages than other bytecode formats. Importantly, it features memory sandboxing and well-defined interfacing through modules, as well as structured control flow to prevent control flow hijacking. The original use-case of WebAssembly was to bring the high-performance of low-level languages such as C and Rust to the web.

The execution of a WebAssembly program is described by the small step reduction relation \hookrightarrow_i over a configuration triple representing the state of the VM, where i indicates the index of the current executing module. The index i is necessary since WebAssembly can load multiple modules at a time. A

configuration contains one global store s , the local values v^* and the active instruction sequence e^* being executed. The rules are of the form $s; v^*; e^* \hookrightarrow_i s'; v'^*; e'^*$. A more detailed overview of the WebAssembly specification can be found in Appendix C.

3.8.2 Remote Debugging Extensions

To formalize our debugging system, we extend the operational semantics of WebAssembly with the necessary remote debugging constructs. The goal of these extensions, is to provide constructs that are as lightweight as possible while still being powerful enough to provide the most common remote debugging facilities. We follow the recipe for defining a debugger semantics as outlined by Torres Lopez et al. (2019), where the semantics of the debugger are defined in terms of the underlying language’s semantics: in this case the WebAssembly specifications. One advantage of this approach, is that it leads to a very concise description of the debugger semantics. More importantly, with this recipe you get a debugger whose semantics are observationally equivalent to those of the underlying language’s semantics. This means that the debugger does not interfere with the underlying semantics, and therefore, only observes real executions. Or more precisely, any execution in the WAR-Duino debugger corresponds to an execution of a WebAssembly program, and conversely that any execution of a program is observed by the debugger. The recipe also makes it straightforward to proof this non-interference of the debugger, as we will show in Section 3.8.3.

At the top of Figure 3-3 we give an overview of our syntactic extensions to the operational semantics of WebAssembly that provide remote debugging support. In the semantics we abstract away the underlying communication primitives, we assume that there is a system in place that reads messages from a stream and places them in the inbox. A concrete implementation may allow communication over the serial port, an HTTP connection or the SPI bus. For ease of exposition all these possible communication methods are modeled through messages msg .

To differentiate the debugger semantics from the underlying language, we write the reduction relation as $(\hookrightarrow_{d,i})$, where d indicates the debugging semantics and i is still the index for the currently executing module. But thanks to how we define the debugger semantics, the operation of a program during debugging is described by the combined reduction rules from the WebAssembly semantics and our debugger semantics.

The semantics of the debugger consists of a state transitioning system where each state consists of a debugger state dbg , zero or more local values v^* and a focused operation e^* . The main state of the debugger dbg is represented

$$\begin{array}{l}
 (\text{Debugger State}) \quad \text{dbg} ::= (\text{es}, \text{msg}_i, \text{msg}_o, s, \text{bp}) \\
 (\text{execution state}) \quad \text{es} ::= \text{play} \mid \text{pause} \\
 (\text{Messages}) \quad \text{msg} ::= \emptyset \mid \text{play} \mid \text{pause} \mid \text{step} \mid \text{dump} \mid \text{break}^+(\text{id}) \mid \text{break}^-(\text{id}) \\
 \\
 \frac{s; v^*; e^* \hookrightarrow_i s'; v'^*; e'^* \quad \text{id}(e^*) \notin \text{bp}}{(\text{play}, \emptyset, \emptyset, \text{bp}); s; v^*; e^* \hookrightarrow_{d,i} (\text{play}, \emptyset, \emptyset, \text{bp}); s'; v'^*; e'^*} \text{ vm-run} \\
 \\
 \frac{s; v^*; e^* \hookrightarrow_i s'; v'^*; e'^*}{(\text{pause}, \text{step}, \emptyset, \text{bp}); s; v^*; e^* \hookrightarrow_{d,i} (\text{pause}, \emptyset, \emptyset, \text{bp}); s'; v'^*; e'^*} \text{ db-step} \\
 \\
 \frac{s; v^*; e^* \hookrightarrow_i s'; v'^*; e'^*}{(\text{pause}, \text{dump}, \emptyset, \text{bp}); s; v^*; e^* \hookrightarrow_{d,i} (\text{pause}, \emptyset, \text{msg}, \text{bp}); s'; v'^*; e'^*} \text{ db-dump} \\
 \\
 \frac{}{(\text{es}, \text{pause}, \emptyset, \text{bp}); s; v^*; e^* \hookrightarrow_{d,i} (\text{pause}, \emptyset, \emptyset, \text{bp}); s; v^*; e^*} \text{ db-pause} \\
 \\
 \frac{}{(\text{pause}, \text{play}, \emptyset, \text{bp}); s; v^*; e^* \hookrightarrow_{d,i} (\text{play}, \emptyset, \emptyset, \text{bp}); s; v^*; e^*} \text{ db-pause} \\
 \\
 \frac{}{(\text{es}, \text{break}^+(\text{id}), \emptyset, \text{bp}); s; v^*; e^* \hookrightarrow_{d,i} (\text{es}, \emptyset, \emptyset, (\text{bp} \cup (\text{id}))); s; v^*; e^*} \text{ db-bp-add} \\
 \\
 \frac{}{(\text{es}, \text{break}^-(\text{id}), \emptyset, \text{bp}); s; v^*; e^* \hookrightarrow_{d,i} (\text{es}, \emptyset, \emptyset, (\text{bp} \setminus (\text{id}))); s; v^*; e^*} \text{ db-bp-rem} \\
 \\
 \frac{\text{es} \neq \text{pause} \quad \text{id}(e^*) \in \text{bp}}{(\text{es}, \text{break}^-(\text{id}), \emptyset, \text{bp}); s; v^*; e^* \hookrightarrow_{d,i} (\text{es}, \emptyset, \emptyset, (\text{bp} \setminus (\text{id}))); s; v^*; e^*} \text{ db-bp-rem}
 \end{array}$$

Figure 3-3. Core debugger semantics. Small step reduction rules ($\hookrightarrow_{d,i}$) for the WARDuino remote debugger, as extensions to the WebAssembly semantics as defined in Haas et al. (2017).

as a 5-tuple that holds the execution state es, the last incoming message msg_i, the last outgoing message msg_o, the WebAssembly store s and, a set of breakpoints bp. The execution state indicates whether the virtual machine is paused (PAUSE) or running (PLAY). Rules for setting msg_i when messages are received, and for clearing msg_o when delivering outbound messages are omitted from our semantics as these are dependent on the communication method. The reduction rules for remote debugging are shown in the lower part of Figure 3-3, we describe them below.

vm-run When in the PLAY state with no incoming or outgoing messages and no applicable breakpoints, the debugger takes one small step of the small step operational semantics \hookrightarrow_i . That is, a regular WebAssembly step is taken.

db-pause When the debugger receives a *pause* message, the debugger transitions to the PAUSE state. Note that it is allowed to transition from any previous state to the paused state. After transitioning to the paused state, the rule VM-RUN is no longer applicable.

db-dump In the paused state the debugger can request a dump of the virtual machine's state. This dump is communicated to the debugging host by an outgoing message, which contains the full WebAssembly state and the breakpoints of the debugger.

db-run When the debugger is in the PAUSE state, the programmer can restart execution by sending a *run* message.

db-step When the debugger receives the step message in the PAUSE state, it takes one step (\hookrightarrow_i). The debugger remains in the PAUSE state.

db-bp-add Breakpoints can be added in any run state.

db-bp-rem Breakpoints can be removed in any run state.

db-break When the debugger is not in the PAUSE state, and the id of the currently executing expression is in the list of breakpoints the debugger transitions to the PAUSE state.

It is important to note that the DB-DUMP adds a message to the outgoing messages, but the other rules expect the outgoing messages to be empty. Since the communication is abstracted away, we assume that incoming and outgoing messages are added and removed by an external system, and the debugging semantics cannot get stuck. In other words, the other rules in the semantics only handle incoming messages after all the outgoing messages are removed by the external communication system.

Below, we show three derived commands for stepping through the WebAssembly code after a breakpoint is hit. These are not written as rules in our formal semantics as they are simply a combination of the rules we already introduced.

step-into This stepping command is offered only for function calls. In order for the debugger client to verify whether this command should be active it can request a dump of the current execution and enable the step-into command in the GUI. Execution of the STEP-INTO command is the same as DB-STEP.

step-out When the programmer is debugging inside a function, they might want to step out of the function call. Because the end of a function is an actual instruction in WebAssembly the debugger can inspect the body of the function and add breakpoints for all the exit points of the function. Important here is that the debugger needs to take note of the call stack at the moment a STEP-OUT is requested. To handle recursive calls correctly, the program should only be paused if one of the breakpoints is hit while the call stack has the same height. If the breakpoint is hit on a larger call stack, the program should be resumed (by sending play).

step-over Like step-into, step-over only activates for the next call instructions. Instead of following the call the step-over stepping command stops the debugger when the call is finished. The instruction sequence to express step-over with our basic debugging constructs are: take one step to go into the function (DB-STEP), execute the STEP-OUT stepping command.

The semantics allow for more elaborate debugging operations to be build on top of those presented here. However, the previous three operations represent the most widely used debug operations, and should therefore accommodate most developers debugging needs.

3.8.3 Proof of Observational Equivalence

In our original publication (Lauwaerts et al., 2024), we proved observational equivalence between the debugging semantics and the WebAssembly semantics over a single step. This more closely aligns with the definition of observational equivalence in previous work by Torres Lopez et al. (2019). However, the soundness and completeness theorems we apply in future chapters is a stronger form of bisimulation, which in essence proves observational equivalence over a series of steps.

In order to prove the observational equivalence between the debugger semantics and the base language semantics, we use the same proof method as Torres Lopez et al. (2019), which proves observational equivalence by a weak bisimulation argument. With this proof, we show that if an arbitrary WebAssembly program P can take a step to a program P' , the debugging semantics allows the debugger to reach the program P' from the program P by one or more debugging steps. The other way around, if the debugger allows a program P to transition to a program P' , the normal WebAssembly evaluation will also allow the program P transition to the program P' .

In the semantics we leave out the specifics of the communication, and assume the incoming messages are added to the debugging state in the correct order. For the proof, we will reason over a stream of messages instead of a

single one. Thanks to the recipe we follow for the debugger semantics, the proof follows almost directly by construction.

Theorem 3-1. (Observational equivalence) Let S be the WebAssembly configuration $\{s; v^*; e^*\}$, for which there exists a transition (\hookrightarrow_i) to another configuration S' with $\{s'; v'^*; e'^*\}$. Let the debugging configuration $(\{es, msg_i, msg_o, bp\}; s; v^*; e^*)$ with execution state es , incoming messages msg_i , outgoing messages msg_o , and set of breakpoints bp ; be such that processing the stream of incoming message M^* takes exactly one externally visible step (VM-RUN or DB-STEP) in the debugger semantic (\hookrightarrow_e) , then:

$$\begin{aligned} & (\{s; v^*; e^*\} \hookrightarrow_i \{s'; v'^*; e'^*\}) \\ \iff & (\{rs, msg_i, msg_o, bp\}; s; v^*; e^* \hookrightarrow_e \{rs, msg_i, msg_o, s', bp\}; s'; v'^*; e'^*) \end{aligned}$$

The left-hand side of the double implication presents a single step in the normal evaluation (\hookrightarrow_i) of a WebAssembly program, while the right-hand side presents one or more steps in the debugging semantics $(\hookrightarrow_{d,i}^*)$ where only a single step is externally visible (\hookrightarrow_e) . We will start by sketching the proof for the first implication, that is, an evaluation step in the WebAssembly semantics implies an equivalent series of debugging steps.

Proof Sketch. In case the debugger is in the PLAY state, two cases need to be considered. First, if there is no applicable breakpoint, the only applicable rule that is externally visible is the VM-RUN rule. Applying this rule, will transition the state S to S' by construction. Second, a number of internal rules of the debugger can transition the system into a PAUSE state (e.g., DB-PAUSE, DB-BREAK). By assumption, processing the stream of messages M^* leads to exactly one externally visible step. None of the internally visible rules (e.g., DB-PAUSE, DB-BP-ADD) change the underlying state S of the program. This means, that whenever the externally visible step is taken, it will do so with the same underlying state S as at the start of the debugging steps. The only externally visible steps, are DB-STEP and VM-RUN, which take exactly the same transition as the underlying WebAssembly semantics. In case the debugger starts in the PAUSE state, a similar argument holds. \square

Now we will provide the proof sketch for the second implication, that is a series of evaluation steps in the debugger semantics implies an equivalent evaluation step in the WebAssembly semantics.

Proof Sketch. Only the VM-RUN and the DB-STEP rules change the WebAssembly configuration S in the debugging configuration D . By construc-

$$\begin{array}{l}
 (\text{Messages}) \text{ msg} ::= \dots \mid \text{upload } m^* \mid \text{update}_f(\text{id}_i, \text{id}_f, \text{code}_f) \mid \text{update}_l(j, v) \\
 (\text{Closure}) \quad \text{cl} ::= \{\text{inst } i, \text{idx } j, \text{code } f\}
 \end{array}$$

$$\frac{(\vdash m)^* \quad \{s', v'^*, e'^*\} = \text{bootstrap}(m^*)}{\{\text{pause}, \text{upload}(m^*), \emptyset, \text{bp}\}; s; v^*; e^* \hookrightarrow_{d,i} \{\text{pause}, \emptyset, \emptyset, \emptyset\}; s'; v'^*; e'^*} \text{ UPLOAD-M}$$

$$\frac{s' = \text{update}_f(s, \text{id}_i, \text{id}_f, \text{code}_f)}{\{\text{pause}, \text{update}_f(\text{id}_i, \text{id}_f, \text{code}_f), \emptyset, \text{bp}\}; s; v^*; e^* \hookrightarrow_{d,i} \{\text{pause}, \emptyset, \emptyset, \text{bp}\}; s'; v'^*; e^*} \text{ UPDATE-F}$$

$$\frac{\vdash v : \epsilon \rightarrow t \quad \vdash v^* : \epsilon \rightarrow t}{\{\text{pause}, \text{update}_l(j, v'), \emptyset, \text{bp}\}; s; v_1^j v v_2^k; e^* \hookrightarrow_{d,i} \{\text{pause}, \emptyset, \emptyset, \text{bp}\}; s; v_1^j v' v_2^k; e^*} \text{ UPDATE-LOCAL}$$

Figure 3-4. Extension of the debugging rules (Figure 3-3) with safe over-the-air updates.

tion, both rules rely directly on the underlying WebAssembly semantics for transitioning S to S' . \square

3.8.4 Safe Over-the-air Code Updates

Our over-the-air update system allows programmers to upload new programs and to update functions and local variables. Here, we present the system as an extension of the debugger semantics, but the over-the-air updates can also be defined on their own without the debugger as we show in Appendix E.1. Note that the observational equivalence of the debugger semantics will no longer hold with the addition of over-the-air updates, since they allow for arbitrary code changes.

Figure 3-4 gives an overview of the additional reduction rules to dynamically update a WebAssembly program. In these rules the debug messages are extended with three update messages. In order to improve the usability of the semantics, the over-the-air updates can only be executed in the paused state. Additionally, the program will remain in the paused state to allow setting new breakpoints.

upload-m An *upload* message instructs WebAssembly to restart execution with a new set of modules m^* . We require all these modules to be well typed, $(\vdash m)^*$. The meta-function *bootstrap* represents WebAssembly’s initialization procedure, described in the original WebAssembly paper (Haas et al., 2017). Note that this procedure replaces the entire configuration, including the WebAssembly state, locals and stack. Furthermore, upon receiving the *upload* message the debugger state is reset and all breakpoints removed.

As with the debug semantics, rules for setting msg_i are omitted.

update-f The message to update a function specifies the function to update and its new code (code_f). To identify a function we must supply the ID of the instance id_i it lives in and the index it exists at id_f in that instance. The meta-function update_f replaces the function in the state s and validates that its type remains the same.

WebAssembly's formalization transforms every function in a closure that holds its code f and the module instance it was originally defined in. When a function is imported into another module or placed in a table, its closure is copied to the other module instance. Because the closure holds the original instance, it can be executed in the right context. When it calls other functions, for example, these must be the functions from the original module rather than from the calling module. We extended closures with an extra identifier idx , which holds the index of the function in its defining module. Thanks to this, the update_f can replace all closures in s where the inst is id_i and the idx is id_f .

update-local Updating a local is done with an update_l message. This message holds the index of the local to be updated and its new value. We validate that the type of the new value is the same constant type $\epsilon \rightarrow t$ as the original value at the chosen index.

Note that we only allow updates if the underlying types remain the same. While this provides safety, it can still have undesirable effects. For example when updating, in the middle of a recursive function the new base conditions might have already been exceeded. The WARDuino VM does not tackle these kinds of problems. In future work we hope to improve on this by incorporating techniques from work on dynamic software updates (Tesone et al., 2018).

3.8.5 Callback Handling

In Section 3.5.5 we discussed the architecture of our callback handling system. The system follows an event-driven approach, where ordinary WebAssembly functions are registered as callbacks for a specific event. Before we can formalize how callbacks are executed by the WebAssembly runtime, we must extend the abstract syntax with the necessary concepts: events, callbacks, memory slices, and callback mappings. The top part of Figure 3-5 shows how we extend the syntax, starting from the WebAssembly abstract syntax with the additional syntax for callback handling.

We only formalize one callback for one topic, as multiple callbacks, we would need to introduce a new list type.

Figure 3-5 shows how the store s is extended with a callback environment Cbs , which maps event topics to WebAssembly function indices i . To simplify the evaluation rules, we introduce a new administrative label, the callback context Cbs . This label is identical to the local context construct L^k from the WebAssembly semantics, used to simplify reasoning over control flow (Haas

New WebAssembly syntax rules

(Extended WebAssembly store)	$s ::= \{..., \text{callbacks } Cbs, \text{events } evt^*\}$
(Callback environment)	$Cbs ::= \emptyset$
	$Cbs, \text{memslice} \mapsto i$
(Callback context)	$Clb ::= L^0$
(Event)	$evt ::= \{\text{topic memslice}, \text{payload memslice}\}$
(Memory slice)	$\text{memslice} ::= \{\text{start i32}, \text{length i32}\}$
(Extended instructions)	$e ::= ... \mid \text{callback.set} \mid \text{callback.drop}$

New WebAssembly typing rules

$$\frac{}{C \vdash \text{callback.set memslice : i32} \rightarrow \epsilon} \quad \frac{}{C \vdash \text{callback.drop memslice : } \epsilon \rightarrow \epsilon}$$

$$(\text{Contexts}) \quad C ::= \{\text{func } tf^*, \text{global } tg^*, \text{table } n^?, \text{memory } n^?, \text{local } t^*, \text{label } (t^*)^*, \text{return } (t^*)^?\}$$

Figure 3-5. The extended WebAssembly abstract syntax (top), and the typing rules (bottom) for the WARDuino callback handling system.

et al., 2017). We include this new label to clearly delineate callbacks in evaluation rules.

The global store s is further extended with the event queue, events evt^* . The event system captures all asynchronous events, such as hardware interrupts, and reifies them into this universal event queue—similar to the debugging message queue shown before.

Events must contain one topic and one payload, which are both memory slices (*memslices*). A *memslice* refers to an area in WebAssembly linear memory. This buffer of bytes is defined in the syntax as a tuple of numeric values, the start index and the length. So while the buffers will most likely be strings in practice, the formalization intentionally refrains from specifying anything about the memory content. This way we steer clear of trying to add strings to WebAssembly, which is not our goal. The topic of an event corresponds to the unique identifier of a category of events, to which callbacks can subscribe. Additional data of the event can be stored as a second slice of memory, which we refer to as the event’s payload.

To register and deregister new functions in the callback environment, we add two new instructions; `callback.set` and `callback.drop`. Unlike WebAssembly instructions such as `local.get` we cannot use an index space to refer to callback functions, because callbacks are stored in a mapping from strings to table indices. For this reason, the instructions for adding, removing and retrieving

New WebAssembly evaluation rules

$$\begin{array}{c}
 \frac{s_{\text{callbacks}}[\text{topic} \mapsto \text{nil}] = s'_{\text{callbacks}}}{\{s; v^*; (\text{callback.drop topic})\} \hookrightarrow_{d,i} \{s'; v^*; \varepsilon\}} \text{ deregister} \\
 \\
 \frac{s_{\text{callbacks}}[\text{topic} \mapsto j] = s'_{\text{callbacks}}}{\{s; v^*; (\text{i32.const } j)(\text{callback.set topic})\} \hookrightarrow_{d,i} \{s'; v^*; \varepsilon\}} \text{ register} \\
 \\
 \frac{\begin{array}{l} \xi = s_{\text{events}(0)} \\ s'_{\text{events}} = \text{remove}(s_{\text{events}}, 0) \\ s_{\text{callbacks}}(\xi_{\text{topic}}) = \text{nil} \end{array}}{\{s; v^*; e^*\} \hookrightarrow_{d,i} \{s'; v^*; e^*\}} \text{ drop} \quad \frac{\begin{array}{l} \xi = s_{\text{events}(0)} \\ s'_{\text{events}} = \text{remove}(s_{\text{events}}, 0) \\ e'^* = \text{construct_call}(s, \xi) \end{array}}{\{s; v^*; e^*\} \hookrightarrow_{d,i} \{s'; v^*; \text{Clb}[e'^*]e^*\}} \text{ interrupt} \\
 \\
 \frac{\{s; v^*; \text{Clb}[e^*]\} \hookrightarrow_{d,i} \{s'; v'^*; \text{Clb}[e'^*]\}}{\{s; v^*; e^*\} \hookrightarrow_{d,i} \{s'; v'^*; e'^*\}} \text{ callback} \quad \frac{\{s; v^*; \text{Clb}[\varepsilon]\} \hookrightarrow_{d,i} \{s; v^*; \varepsilon\}}{\{s; v^*; e^*\} \hookrightarrow_{d,i} \{s'; v^*; \varepsilon\}} \text{ resume}
 \end{array}$$

Figure 3-6. Small step reduction rules for the WARDuino callback handling system.

callbacks, take a memory *memslice* containing the topic string. Note that the map returns at most one function index for each topic string. We choose to limit the amount of callbacks per topic in this way, because the mapping would otherwise become too complicated for a simple low-level instruction set such as WebAssembly. However, we can achieve the same result for end-users by supporting multiple callbacks at the level of WebAssembly actions instead.

With these syntactic extensions to WebAssembly, we are now able to formalize how events are processed, and callbacks executed. We list the additional small step reduction rules in Figure 3-6. To keep the rules readable, we will shorten *memslices* by simply writing *topic* or *payload* instead of every numeric value. For instance, in the first rule, $s_{\text{events}(0),\text{topic}}$ is a shorter form for: $(\text{i32.const}, s_{\text{events}(0),\text{topic.start}})$ $(\text{i32.const}, s_{\text{evt}(0),\text{topic.length}})$. Similarly, we write the lookup for the table index of a callback function in the short form: $(s_{\text{cbs}}, s_{\text{evt}(0),\text{topic}})$. This expression corresponds with exactly one $(\text{i32.const}$ index) instruction. We describe each of the rules below.

register The register rule adds a new callback to the callback map, which maps a topic to a WebAssembly function index. The *callback.set* instruction takes an immediate memory slice, which corresponds to the topic

string. The instruction updates the callback map for the topic with a function index j , which it takes from the stack.

deregister Callback functions can be removed from the callback map, with the *callback.drop* instruction, which simply takes a memory slice immediate, and removes the entry for the topic corresponding to the memory slice.

drop Whenever the event queue is not empty, the first event is taken from the queue, and its topic is looked up in the callback map. If no callback is registered for the topic, the event is simply dropped by this rule.

interrupt Whenever a popped event does correspond to a registered callback, its topic and payload are placed on the stack as arguments for the callback function. The callback function is called indirectly with its function index. For brevity, we leave out the details of this call construction in this figure, the detailed construction created by the *construct-call* function can be found in the appendix. The call is placed in the dedicated *Clb* label before the current series of instructions, so that the callback can be executed concurrently with the main program.

callback The callback rule is similar to the invoking rule, and allows the WebAssembly runtime to execute the callback within the *Clb* label.

resume The resume rule is triggered when the callback has finished executing, its label is empty, and the WebAssembly runtime can continue executing the program. Callback labels must always reduce internally to ϵ , since no callbacks can have a return value.

Our formalization closely describes the callback handling system as introduced in Section 3.5.5. It does so with a limited amount of reduction rules. We can keep the formalization small because we reuse the existing instruction when adding a callback to the sequence of instructions. Using a smaller set of rules, means it is easier to reason about the formalization and the impact of the extension on WebAssembly. Furthermore, it means implementing the extension in a WebAssembly runtime is less work, because where the formalization reuses parts of the WebAssembly specification, the existing infrastructure of the runtime can likewise be reused.

So far we have not directly mentioned the interaction between the debugger and callback handling system. The operational semantics as presented here, allow for callback instructions to be introduced at any step. This also holds for the debugging steps. During debugging, WARDuino can jump to a callback function whenever it steps to the next instruction. This can lead to confusing behavior, and is the main reason why debugging concurrent programs is so complicated (Torres Lopez et al., 2019). We address this problem in our *stateful out-of-place debugger*, presented in the next chapter (Chapter 4).

3.8.6 Discussion

The small step semantics of WebAssembly precisely defines how a program executes, allowing embedders, such as web browsers or WARDuino, to create different compatible implementations of the same specification. Additionally, the formalization provides a uniform way to propose extensions to the WebAssembly standard. In this section we formalized three extensions to WebAssembly: remote debugging, over-the-air updates and an asynchronous callback handling system. Other runtimes can use our formalizations to implement (some of) these extensions for their embedding of WebAssembly.

Our first extension, remote debugging allows developers to remotely control a WebAssembly runtime. By sending it messages, they can set breakpoints, pause the execution, inspect values and so on. Our formalization is based on a debugging recipe (Torres Lopez et al., 2019) that transforms a language semantics into an observationally equivalent debugger semantics. This means that no execution path observed by the debugger semantics is not observed by the underlying language semantics, and that no execution path observed by the language semantics cannot be observed by the debugger semantics as well. Thanks to the recipe used to construct the debugger semantics, the proof for observational equivalence follows almost directly by construction as shown in our proof sketch.

With our over-the-air update system programmers can safely replace a running WebAssembly module, specific functions or specific locals. We specify that if functions or locals are updated, they must maintain their original type. When uploading entire modules, the new modules must be valid. Over-the-air updates are defined orthogonal to debugging, this allows these two extensions to be used side-by-side or independently of one another. With the addition of over-the-air updates, the debugger semantics are no longer observationally equivalent to the language semantics, since it can now update code arbitrarily. Nevertheless, the semantics are important to show how the system preserves WebAssembly types across updates. Furthermore, we are not aware of any previous attempts to describe over-the-air updates of WebAssembly code, or describe over-the-air updates of binary code with an operational semantic. There is however, a limited body of work that looks into the theoretical aspects of over-the-air updates. We go into further detail on the existing works in Section 3.11.

Our last extension shows how WARDuino can handle asynchronous events in WebAssembly. Hardware interrupts or asynchronous network communication is facilitated by our novel callback handling system. This system allows developers to transparently interrupt an executing WebAssembly program to execute a callback that deals with an incoming event. While the semantics presented here are certainly novel, there are several other proposals for

supporting asynchronous code in WebAssembly. We discuss these works in Section 3.11.

3.9 Tool Support for WARDuino

WARDuino aims to make it easier for programmers to debug applications running on embedded devices. There are several approaches and tools that WARDuino offers in this regard. The virtual machine includes its own remote debugger, while the use of WebAssembly makes it much easier to build emulators. In this section we give a detailed overview of the different tools available for debugging WARDuino applications.

3.9.1 Debugging WARDuino Programs Remotely

Microcontrollers are often not equipped with a screen and keyboard, therefore, we allow programmers to debug their programs remotely. We offer a command line tool and a Visual Studio Code plugin. First, we give an overview of our debugging protocol and the debugger architecture, before we show the VS Code plugin build on top of this debugger.

3.9.1.1 Debugging Protocol

The WARDuino VM facilitates remote debugging by allowing debug messages to be sent over a variety of carriers. We have experimented both with wired (USB) and wireless (Wi-Fi) communication means. In theory any communication channel can be used.

Our protocol consists of a set of instructions sent as messages to the virtual machine. The first byte of each message indicates its type. Depending on the type, the first byte is followed by a byte sequence consisting of the arguments of the messages. When a debug message is received by the microcontroller, it is caught by an interrupt handler. This handler reads the available data and passes it on to the virtual machine. The VM in turn waits for a full debugging package to arrive. Once a package is complete, it is placed in the debugging queue for final processing. The debugging queue is polled before each executed instruction. If a message is present in the queue, the appropriate action is taken.

There are four broad categories of debug messages supported by WARDuino.

1. Basic debugging

The one-byte *play*, *pause* and *step* messages respectively run, pause or step the currently executing program by setting the VM's run state.

The debugger keeps track of the run state that is either PAUSE or RUN. When in the PAUSE state, WARDuino waits for a *play* or *step* message to process the next instruction. In the RUN state, the VM executes normally.

2. Breakpoints

The remote debug messages *break⁺* and *break⁻* carry a pointer to an instruction where a user wishes to PAUSE execution. These breakpoints are stored in a set. The set is checked before each instruction. When a break point is hit, the run state is set to PAUSE, and an acknowledgment is sent to the remote debugger.

3. Inspection

When a *dump* message is received, the run state is set to PAUSE and a JSON representation of the state of the virtual machine is sent back to the user. The JSON object obtained from a *dump* message contains the call stack, a list of functions, and the current instruction pointer. An example output is shown in

4. Over-the-air updates

The remote debug messages for over-the-air updates, *update_f* and *update_l*, both contain the ID of the function or local to update, and its new value. The virtual machine should be in the PAUSE state to process such as change. Updating a local simply updates the appropriate value on the stack. Updating a function on the other hand is slightly more elaborate. First, the bytecode of the function is parsed and the appropriate structures are built. If the new function has an identical type, the pointer in WARDuino's function table is replaced with a reference to the new code. Any running call of the existing function will continue to work with the old code. New calls will use the updated code.

3.9.1.2 Visual Studio Code Debugger

The remote debugging system we presented so far, allows developers to debug WebAssembly code on microcontrollers remotely via a terminal. Debugging via a terminal with memorized commands is something few developers are used to. Instead, most developers use debuggers with a user-friendly interface such as the GUI debugger in an IDE. We created a plugin for the widely used IDE Visual Studio Code (VSCode) that allows developers to remotely debug WARDuino instances.

At its core, a debugging plugin for an IDE sends the debug messages described above on behalf of the developer. This removes the need for them to know our specific debugging API. Having a plugin send the same messages as a

Tool Support for WARDuino

The screenshot shows the VS Code interface with the WARDuino extension. The main area displays the source code for a WebAssembly file named 'blink.wast'. The code is a simple 'Blink' program. Line 28 is highlighted in yellow, indicating the current execution step. The sidebar on the left contains sections for VARIABLES, WATCH, CALL STACK, and BREAKPOINTS. The CALL STACK section shows the stack trace with 'blink.wast' at the top, followed by 'module'. The bottom status bar indicates the connection is established ('Connected to board'), the line number ('Ln 28'), and the character position ('Col 1').

```
File Edit Selection View Go Run Terminal Help
D Debug WARD ...
blink.wast x Settings
Variables
Locals delay: 1000
Globals
WATCH
CALL STACK PAUSED ON STEP
blink blink.wast 28
module blink.wast 1
Breakpoints
Connected to board Ln 28, Col 1 Spaces:2 UTF-8 LF WebAssembly
master 0 0 0 Debug WARDuino (TestSource) Live Share
```

```
1 (module
2   ; Type declarations
3   (type $int32->int32->void (func (param $int32 i32) i32))
4   (type $int32->void (func (param $int32 i32)))
5   (type void->void (func))
6
7   ; Imports from the WARDuino VM
8   (import "env" "chip_delay" (func $env.chip.delay (type $int32->void)))
9   (import "env" "chip_pin_mode" (func $env.chip.pin_mode (type $int32->int32->void)))
10  (import "env" "chip_digital_write" (func $env.chip.digital_write (type $int32->int32->void)))
11
12  ; Non-mutable globals
13  (global $led $int32 {i32.const 23})
14  (global $on $int32 {i32.const 1})
15  (global $off $int32 {i32.const 0})
16
17  (func $init (type void->void) ; Set pin mode function (private)
18    global.get $led
19    i32.const 2
20    call $env.chip.pin_mode
21
22  (func $blink (type void->void) ; Blink function (public)
23    ; Declare local $delay
24    (local $delay $int32)
25    i32.const 1000
26    local.set $delay
27
28    call $init ; initialise
29
30    ; Blink in infinite loop
31    loop $infinite
32      global.get $led
33      global.get $on
```

Figure 3-7. Screenshot of the VS Code debugger extension for WARDuino with a WebAssembly program (blinking LED).

developer would in the terminal, is enough to support WebAssembly level debugging in an IDE. Figure 3-7 shows a screenshot of the VS Code plugin debugging a remotely running WebAssembly blink program that is currently paused on the highlighted line (Line 28). The plugin also support provisional source mapping for AssemblyScript, which means most features of the plugin can be used to debug AssemblyScript code directly. The buttons at the top of the screen allow the execution to be resumed and steps to be taken. In the sidebar on the left we can inspect local variables and edit them. These edits are then immediately propagated to the device with a *update_t* message. At the bottom of the sidebar, we can inspect the call stack.

3.9.2 Building Emulators

A common practice in IoT development is to use emulators to verify, as well as possible, the correctness of the code before running it on the custom hardware (Makhshari and Mesbah, 2021). Emulation is designed to minimize the need for debugging on microcontrollers. Unfortunately, this approach is far from ideal as non-trivial differences between the emulator and the real device will exist. Emulated sensors may for example not produce real-world values. Instead, they might report a fixed value that does not change over time. Furthermore, real changes in sensor values may appear differently to real devices due to physical effects such as contact bounce (chatter). These differences can cause an application that works in an emulator not to work on a real device. That is why the WARDuino project focuses on delivering an alternative approach, where testing can be performed on the custom

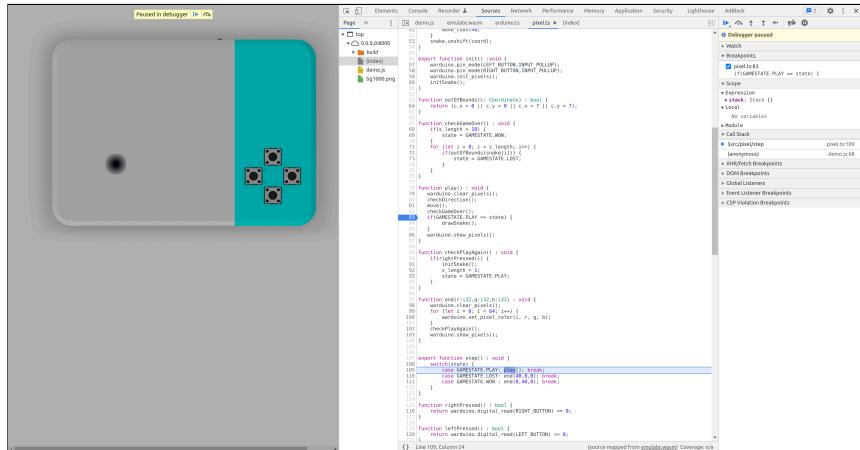


Figure 3-8. Screenshot of a browser-based emulator for custom hardware. The right side of the screenshot shows how the browser debugger can pause and step through the original AssemblyScript code written for WARDuino.

hardware itself. We argue, that this approach can catch more errors than emulation, and leads to a shorter development cycle.

However, emulated verification can still be useful. This is certainly the case when developers work with highly specific hardware, which may not always be at hand. WARDuino also helps when using the emulation approach, providing an easy workflow for implementing emulators for custom hardware.

Developers using WARDuino compile their programs to WebAssembly, which means their code also runs in web browsers. The only missing components are the WARDuino primitives that control the custom hardware. In other words, implementing an emulator for custom hardware comes down to creating a HTML based device and writing a minimal set of hooks to substitute the WARDuino primitives.

Our ESP32-powered game controller is based on Jo
han Von Konow's Sokoban Day design.

We implemented a snake game for a custom game controller that uses an 8x8 LED matrix. To support this LED matrix peripheral, we extended the WARDuino virtual machine with the Arduino Adafruit NeoPixel library² using the process described in section Section 3.7.1. We wrote a snake game in AssemblyScript. To implement the emulator we write small JavaScript functions for each primitive we use in the code. The entire JavaScript code for the emulator consists of only 150 lines. It allows us to run the snake game in the browser. Additionally, we can use the browser's debugger to step through the AssemblyScript code, as shown in Figure 3-8.

²see: <https://www.arduino.cc/reference/en/libraries/adafruit-neopixel/>

3.9.3 Debugging High-Level Languages

Debugging at the low level of WebAssembly is not workable for any real-world application. Our goal is to debug the high-level source code. So-called “source maps” make this possible. Source maps align the line numbers of the original code to the WebAssembly instructions they compile to. They typically come as a separate file containing only the mapping. By cross-referencing WARDuino’s instruction pointer with the source maps, we can derive the line we are executing in our program written in a high-level language.

Figure 3-8 shows source mapping in action, the emulator is executing WebAssembly, but the code view on the right shows AssemblyScript code. The WebAssembly instruction pointer is translated into a line number in the AssemblyScript code by using source maps. AssemblyScript is not the only language with source mapping. Most high-level languages with good support for WebAssembly, can generate a source map during compilation. In fact, any language using the LLVM compiler infrastructure, can generate all the necessary information in DWARF format from which a source map can be derived.

3.10 Evaluation

In this section we evaluate the WARDuino VM in terms of its runtime performance, and conformance to the WebAssembly standard. Section 3.10.1 illustrates the usability of WARDuino in the real world, by presenting a qualitative evaluation of a smart light application written in AssemblyScript (Section 3.10.1). Next, in Section 3.10.2, we evaluate the performance of the virtual machine with a set of microbenchmarks. We measure the runtime speed, as well as, the size of executables. Since WARDuino targets microcontrollers with limited memory, it is important to take into account the number of bytes that get flashed per program. We end the section by looking at WARDuino’s conformity to the WebAssembly standard (Section 3.10.3).

3.10.1 Practical Application

Smart light applications are one of the most widely known and practically applied IoT applications. We investigate how well WARDuino performs for programming microcontrollers in practice by implementing a simple smart light application in AssemblyScript. Specifically, we connected an ESP device to a button, and an LED. The microcontroller will toggle the LED, when the button is pressed, or when it receives a certain MQTT message over the internet. To receive MQTT messages, it subscribes to the “LED” topic on an MQTT broker. There are two recognized MQTT payloads: “on” and “off”.

```
1 import * from "as-warduino";
2
3 const BUTTON = 25; const LED = 26;
4 const SSID = "local-network";
5 const PASSWORD = "network-password";
6 const CLIENT_ID = "random-client-id";
7
8 function until(attempt: () => void,
9               done: () => boolean): void {
10    while (!done()) {
11      delay(1000); attempt();
12    }
13}
14
15 function callback(topic: string,
16                   payload: string): void {
17  print("Message [" + topic + "] " + payload);
18
19  // Inspect the payload of the MQTT
20  // message
21  if (payload.includes("on")) {
22    digitalWrite(LED,
23                PinVoltage.HIGH); // On
24  } else {
25    digitalWrite(LED,
26                PinVoltage.LOW); // Off
27  }
28}
29
30 function toggleLED(_t: string, _p: string): void {
31  let status = digitalRead(LED);
32
33  // Toggle LED via MQTT
34  MQTT.publish("LED", status ?
35              "off" : "on");
36
37  // Connect to Wi-Fi
38  until(() => { WiFi.connect(SSID,
39                      PASSWORD); },
40        WiFi.connected);
41  let message = "Connected to wifi
42  with ip: ";
43
44  print(message.concat(WiFi.localip()));
45
46  // Connect to MQTT broker
47  MQTT.init("192.168.0.42", 1883);
48  until(() =>
49  { MQTT.connect(CLIENT_ID); },
50        MQTT.connected);
51
52  // Subscribe to MQTT topic and turn
53  // on LED
54  MQTT.subscribe("LED", callback);
55  MQTT.publish("LED", "on");
56
57  // Subscribe to button interrupt
58  interruptOn(BUTTON,
59              InterruptMode.RISING,
60              toggleLED);
61
62  while (true) {
63    until(() =>
64    { MQTT.connect(CLIENT_ID); },
65          MQTT.connected);
66    MQTT.poll();
67    delay(500); // Sleep for 0.5
68    seconds
69  }
70}
```

Listing 3-9. A smart light AssemblyScript program for WARDuino.

Listing 3-9 shows the source code of the software running on the ESP. On the left side, we import the WARDUINO primitives, and we define some constants and helper functions. On the right side, we have the main entry point of the program, starting at [Line 31](#). The main function first sets the correct modes of the LED and BUTTON pins. Next, it connects to the Wi-Fi network and prints the local IP address of the device on success ([Lines 36–39](#)). When the microcontroller is connected to the network, it connects to the MQTT broker ([Lines 39–47](#)). In Section 3.4.1, we already discussed the code required to set up these connections.

With an established connection, the microcontroller subscribes to the “LED” MQTT topic on [Line 47](#). The supplied callback is defined on [Lines 14 to 24](#). It takes two arguments, the topic and the payload of the incoming message. First, it prints the message to the serial port using `print`. Then, we inspect the payload, if it is the string “on”, we turn the LED on by using `digitalWrite`, otherwise we turn the LED off.

After subscribing, the `main` function sends an “on” message to the “LED” topic using the `MQTT.publish` primitive. When the device receives its own message, the callback function will make the LED shine.

On [Line 47](#) we attach a callback to rising voltage changes of the button pin. We use the `interruptOn` primitive to do this. It takes three arguments: the pin to monitor, the kind of change to trigger for, and a callback to invoke when a change occurs. Here we monitor the pin of the button for a rising edge (`InterruptMode.RISING`). This means our callback, `callback`, will be invoked whenever the `BUTTON` pin goes from low (not pressed) to high (pressed). [Lines 26 to 30](#) define `toggleLED`. It reads the current state of the LED and then sends out an MQTT message with the opposite state. This message will then be received by `callback`, which in turn toggles the LED’s state.

The `main` function concludes by ensuring that the connection to the MQTT broker stays alive. To this end, it uses a `while` loop that calls `until` to reconnect to the MQTT broker if the connection is lost.

Note that the two callbacks used in this example, `callback` and `toggleLED`, have different types. However, in [Section 3.8.5](#) we saw that our callback system requires that all stored callbacks have the type $i32 \times i32 \times i32 \times i32 \rightarrow \varepsilon$. This is indeed the case at the WebAssembly level. The primitive behind `interruptOn` requires a callback of that type. Our language interoperability layer abstracts this away and exposes an `interruptOn` that expects a `void → void AssemblyScript` callback.

To test the stability of WARDuino, we run the code in Listing 3-9 on an ESP32-DevKitC V4 board with WARDuino. We also create a small web application to control the LED from our phone via MQTT. When testing our setup, we encountered no noticeable delay between pressing the physical button, and the LED changing status. Furthermore, the delay between pressing the button on the web page, and the LED updating was reasonable and mostly influenced by the Wi-Fi connection.

3.10.2 Performance on Microcontrollers

There are three ways in which developers can run programs on microcontrollers. Dynamically typed languages such as JavaScript are run in dynamic runtimes, while statically typed languages can be executed with a byte-code interpreter, as is the case for WebAssembly, or can be compiled to executable byte-code, typically done with C or C++. In this section we compare the general computational performance of the WARDuino virtual machine with each approach. For the dynamic language we used the popular Espruino (Williams, 2014) runtime for JavaScript. For the static runtime we compared WARDuino with another WebAssembly byte-code interpreter that is small enough to run on microcontrollers, namely WASM3 (Massey and Shymanskyy, 2021). Since it is still the most widely used language for microcontrollers, we used C as the compiled language. We use each approach to run the same microbenchmarks on a microcontroller. Since we are interested in comparing the general computational performance and memory occupancy of our approach, our benchmarks consist of standard computational tasks; such as calculating the greatest common divisor, factorial, binomials, Fibonacci sequence, or verifying if a number is prime.

Espruino (Williams, 2014) is a commercial JavaScript based microcontroller platform for IoT applications. Like WARDuino, Espruino is a VM that runs on microcontrollers. Instead of running WebAssembly, it interprets JavaScript, a popular programming language. The pins of the device are exposed as global JavaScript objects with methods for adjusting their value, D14.set() for example makes pin D14 high. Other features, such as Wi-Fi connectivity, can be imported and present themselves as JavaScript objects as well.

WASM3 (Massey and Shymanskyy, 2021) is a fast WebAssembly interpreter, which uses a special compilation technique rather than JIT compilation (Aycock, 2003) to achieve good performance. It has explicit support for microcontrollers such as the ESP32 (Espressif Systems, 2023b). Similar to WebAssembly it exposes access to the hardware of the microcontroller through a custom WebAssembly module that provides Arduino primitives. Our benchmark consists of six computationally intensive programs implemented in JavaScript (for Espruino), WebAssembly (for WARDuino and WASM3), and C (as baseline). The WebAssembly code was generated from C code with Clang 13 (Clang contributors, 2021). To ensure an honest comparison this C code is identical in structure to the JavaScript code except for the addition of types. Additionally, we prohibited the compiler to perform loop unrolling and inlining of the benchmark functions. Appendix E.2 describes our microbenchmark functions in detail. Each solves some mathematical problem in a naive way.

Evaluation

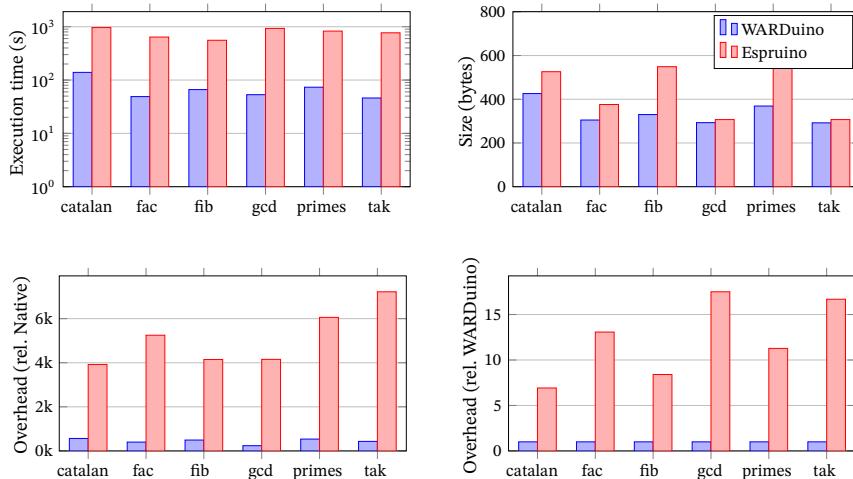


Figure 3-9. The execution times of WARDuino and Espruino. *Top Left:* absolute execution times for the benchmarks. *Top Right:* sizes of the programs uploaded to the VM. *Bottom Left:* execution time normalized to native C execution time. *Bottom Right:* execution times normalized to the WARDuino execution time.

We compare the performance of the runtimes in terms of execution speed and program size for each microbenchmark. When measuring the execution speed, we record the execution time of the benchmarks excluding the upload and initialization time of the virtual machines. We include the program size, because the low-end microcontrollers we are targeting have very limited memory. In fact, the measurements were performed on an ESP32-DevKitC V4 board³. This board features an ESP32 WROVER IE chip that operates at 240 MHz, with 520 KiB SRAM, 4 MB SPI flash and 8 MB PSRAM. This is a representative board for the kind of resource-constrained microcontrollers targeted by WARDuino. There exist more resource-rich devices that are used for IoT applications, such as the Raspberry Pi devices, but these are so powerful that many of the challenges outlined in this chapter are present to a far lesser extent. For example, as a Raspberry Pi has a full-fledged operating system, it is trivial to adapt the code remotely (with ssh).

3.10.2.1 Espruino

Figure 3-9 shows the results of the benchmarks for Espruino and WARDuino. In each graph the green (right) bars indicate the measurements for Espruino,

³see: <https://docs.espressif.com/projects/esp-idf/en/latest/esp32/hw-reference/esp32/get-started-devkitc.html>

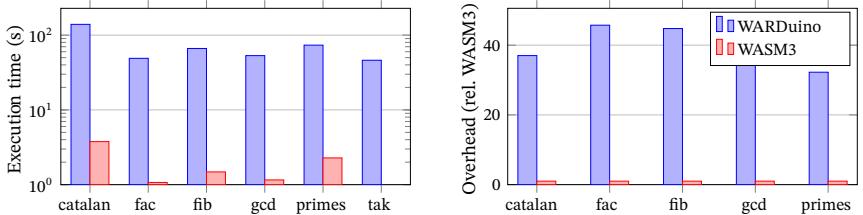


Figure 3-10. The benchmark execution times of WARDuino and WASM3. *Left:* absolute execution times. *Right:* execution times normalized to WASM3 execution time.

the red (left) bars show the results for WARDuino. The first graph, on the top left, shows the absolute execution times of each benchmark on a log scale. The overhead of the WARDuino and Espruino implementations compared to execution time of a native C implementation are shown in the graphs at the bottom. We see that WARDuino consistently outperforms Espruino by roughly a factor of 10. In fact, the geometric mean of the overhead relative to WARDuino is 11.66. Note that the difference is even larger for the `tak` benchmark. This may be attributed to the extreme amount of recursion the `fib` benchmark exhibits. This suspicion seems to be confirmed by the (iterative) `fib` benchmark that calculates Fibonacci numbers without recursing. In this benchmark the performance difference is indeed less pronounced as in the `tak` benchmark.

In the last graph (top right) we show the byte code sizes uploaded to the instantiated virtual machines. We see that the WARDuino size is never larger than the JavaScript files. This is not surprising, as WebAssembly programs are saved in a binary format, and were optimized for size by the compiler.

3.10.2.2 WASM3

Figure 3-10 compares the performance of WASM3 and WARDuino. The graph on the right side shows the overhead of the WARDuino virtual machine relative to the WASM3 runtime. We see that WASM3 executes the same WebAssembly program approximately forty times faster than WARDuino, to be precise, the geometric mean of WARDuino's overhead compared to WASM3 is 40.75.

Although WASM3 is faster than WARDuino, the interpreter's architecture, comes with a significant drawback on memory-constrained devices. It trades memory space for time. Our `tak` benchmark cannot run on the ESP32 with WASM3 because the device runs out of memory. In contrast, this benchmarks runs well on WARDuino. We excluded the `tak` benchmark from the second

	Espruino (s)	WARDuino (s)	WASM3 (s)	C (s)	$\frac{\text{Espruino}}{C}$	$\frac{\text{WARDuino}}{C}$	$\frac{\text{WASM3}}{C}$
catalan	964.72	139.38	3.765	0.246	3922.54	566.71	15.31
fac	640.11	48.97	1.071	0.122	5248.21	401.49	8.78
fib	557.39	66.33	1.481	0.134	4145.68	493.35	11.02
gcd	931.1	53.21	1.157	0.224	4153.24	237.34	5.16
primes	828.54	73.48	2.279	0.137	6058.18	537.29	16.66
tak	769.6	46.14	—	0.107	7217.92	432.7	—
mean	767.48	65.87	1.74	0.15	4993.28	428.54	10.5

Figure 3-11. Left: Absolute execution times in seconds for all tests. Right: Execution time of tests normalized to the native C implementation. The means shown in the table are geometric means.

graph in Figure 3-10 for this reason. Note that the WebAssembly program implementing tak does run on the same device with WARDuino.

3.10.2.3 Comparison

The complete benchmarks results are shown in Figure 3-11. In the first four columns of the table, we report the time that elapses between starting and ending the execution of the microbenchmark ten times for each platform. On the right, we list the execution times normalized to the execution time of the native C implementation. Because the C implementation does not run in a managed environment, it is much faster. To add two numbers for example, no stack access is needed in native C. Since WebAssembly is a stack machine, and our implementation does not yet feature a JIT compiler, memory access is required to perform all basic operations. Taking the geometric mean of the normalized execution times, shows that WASM3 is 11 times slower than its native C, while WARDuino is about 428 times slower and Espruino is 4992 times slower. We note that clang was instructed to optimize for size. Setting the compiler to optimize more at the cost of binary size can have a big impact on the performance of WARDuino at the price of binary size code. Not optimizing for binary size reduces WARDuino’s overhead compared to C to 312x.

3.10.3 Conformance to the WebAssembly Standard

The WebAssembly working group provides a test suite for the core WebAssembly semantics⁴. These integration tests are meant to help runtime implementers verify that their implementation follows the official specifica-

⁴github.com/WebAssembly/spec/tree/main/test/core

tions. Each test contains a WebAssembly module to be loaded by the virtual machine, and a sequence of assertions to check. These assertions specify an action to execute on the module, and the expected result.

We used the official specification test suites to test the WARDuino virtual machine extensively. Because WARDuino does not yet support the latest extending proposals, we use the 15295 tests of the latest specification test suite that only test the original core specification. For instance, we leave out the tests for SIMD instructions, since this proposal has not been adopted by the WARDuino virtual machine. Besides the official specifications, we wrote our own specification test for the WARDuino primitives and extension. Analogous to the official tests, we use these tests to verify that our primitives do not cause ill-formed stacks and only throw traps under the right conditions.

3.10.4 Discussion

The computational benchmarks in this section show that WARDuino is roughly ten times faster than the popular Espruino virtual machine. While IoT applications typically do not perform many computationally heavy tasks, we believe that the difference in performance for these benchmarks is significantly large enough to show that WARDuino—and WebAssembly generally—can easily outperform dynamic interpreters for high-level languages. At the very least, we may conclude that WARDuino is certainly fast enough for real-world IoT applications, such as those run with Espruino. This is further illustrated by the smart light application at the beginning of this section, which shows that WARDuino can indeed be used to program embedded devices with AssemblyScript.

The microbenchmarks also show that WARDuino executes programs significantly slower than their native counterparts. The extra execution time allows us to provide the developer with the safety guarantees of WebAssembly and features such as remote debugging and over-the-air updates. Measurements of the WASM3 virtual machine show that WebAssembly program can run faster in WASM3 on microcontrollers than in WARDuino. While WARDuino has a significant overhead in speed compared to WASM3, it does manage to run with a lower memory footprint, as WASM3 is not able to run all our benchmarks without exceeding the memory limits of our microcontroller. Additionally, WASM3 also does not enable remote debugging and over-the-air updates. Nevertheless, we believe that we could use techniques from WASM3 to further improve WARDuino’s performance.

Aside from performance, we have shown that WARDuino conforms to most of the core WebAssembly specification.

3.11 Related Work

WARDuino presents a WebAssembly virtual machine for microcontrollers and a collection of extensions to the WebAssembly standard. In this section we discuss the related work for each aspect in turn. We focus first on programming microcontrollers with non-WebAssembly solutions. Then we discuss other WebAssembly embeddings for microcontrollers. After this, we finish our related work by summarizing the alternative methods for handling interrupts in WebAssembly.

Programming Embedded Devices

The world of programming languages for microcontrollers is heavily dominated by the C language (Kernighan and Ritchie, 1989), but an increasing range of programming languages have been ported to various hardware platforms, such as: Forth (Rather and Moore, 1976), BASIC (Kemeny et al., 1968), Java (Gosling et al., 1996), Python (Rossum, 1995), Lua (Ierusalimschy et al., 1996) and Scheme (Yvon and Feeley, 2021). Here we restrict ourselves to compare popular implementation approaches for IoT functionality on ESP-based microcontrollers, the platform on which WARDuino was primarily tested.

The predominant programming language for programming the ESP processor is C (Espressif Systems, 2023a, Kernighan and Ritchie, 1989). The advantage of using C is that the programs execute fast. The downside is that it places the burden of managing memory onto the developer. Another downside of the C language is that once a bug is potentially solved, the programmer needs to re-compile, flash the hardware and restart the device completely. Flashing the chip can take a long time, making the development of microcontroller software a rather slow process.

Remote Debugging Embedded Devices

Remote debugging is widely used in embedded systems (Pötsch et al., 2017, Skvač Bőžic et al., 2024, Söderby and De Feo, 2024) and typically follows one of two approaches: stub or on-chip debugging (Li et al., 2009). A stub is a lightweight software module running on the microcontroller that instruments the program, whereas on-chip debugging employs dedicated hardware—such as JTAG-based debuggers (“IEEE Standard for Test Access Port and Boundary-Scan Architecture,” 2013)—to facilitate the process. These hardware debuggers can integrate with various software tools (Söderby and De Feo, 2024), including the popular OpenOCD debugger (Högl and Rath, 2006). Using hardware debuggers is not easy, and is mostly used to debug

programs written in low-level programming languages such as C and C++. Additionally, there are several security concerns with JTAG interfaces (Lee et al., 2016, Vishwakarma and Lee, 2018) by for instance allowing attackers to reverse engineering the microcontroller’s software.

None of these remote debuggers are particularly easy to set up. Only recently did we see the first IDE integration with the release of the Arduino IDE 2.0 at the end of 2022. The new version comes with a debugger interface that allows developers to debug C and C++ code with standard debugging operations. It does not support any over-the-air updates (Söderby and De Feo, 2024). Subsequently, developers still need to flash the entire software at every change. In contrast, WARDUINO allows both remote debugging and over-the-air updates to ease program development on ESP processors.

Virtual machines for Embedded Devices

To provide a more modern programming experience, several virtual machines (VMs) tailored for microcontrollers have been developed to abstract away the complexities of low-level programming, and provide stubs for remote debugging capabilities—to replace the hardware debuggers. We go over some notable examples here.

The Zerynth Virtual Machine (Zerynth s.r.l., 2021) allows developers to run Python programs on 32-bit microcontrollers, but it mainly targets the ESP platform. Users can send HTTP and MQTT request by using the Zerynth standard library. Like our work, these network primitives are implemented in C and exposed in a (Python) module. Zerynth only supports Python, whereas WARDUINO aims to build a common WebAssembly based intermediate representation that allows a multitude of languages to use the networking capabilities of the embedded device. Additionally, WARDUINO supports remote debugging with breakpoints, a capability the Zerynth VM does not offer.

Espruino (Williams, 2014) allows programmers to use a dialect of JavaScript by running a JavaScript interpreter on the chip. The VM is unfortunately too slow to program the device drivers in JavaScript. Therefore, most support for displays and sensors is hard-coded in the Espruino VM. Espruino has MQTT and HTTP modules that can be used in the traditional callback-based style of JavaScript. The VM offers both a web IDE, and a command-line tool to program microcontrollers. Both applications offer roughly the same functionalities, and can connect to a remote device over many connection types, such as serial, Wi-Fi, or Bluetooth. Once connected to a device, Espruino can provide the developer with a REPL to execute JavaScript code directly on the device. This way Espruino does support over-the-air updates. The Espruino

runtime contains a built-in remote debugger, which uses the same commands as GDB.

MicroPython (George, 2021) is a highly optimized subset of the Python programming language. It provides on-the-chip compilation of Python programs. MicroPython supports HTTP requests through its `urequests` module and MQTT with the `micropython-mqtt` community package. The MicroPython project does not provide any means for remote debugging itself, but does offer a REPL in the browser that can connect with embedded devices over serial or Wi-Fi (George, 2021). However, there are a few integrated development environments for Python that can use MicroPython, such as the Mu (Tollervey, 2022) and Thonny (Annamaa, 2015) editors, which do support minimal remote debuggers. Unfortunately, both debuggers only support larger Raspberry Pi devices, and do not appear to support smaller microcontrollers targeted by WARDuino.

There are multiple projects for using Ruby on embedded devices, the most widely used and actively maintained is mruby (Yukihiro and others, 2023). The mruby project partially implements the ISO standard for the Ruby language. Unfortunately, mruby does not support a remote debugger for embedded devices and developers are forced to rely on print-statement debugging. The project does include its own package manager, which gives developers access to a variety of libraries for accessing hardware and using IoT protocols (Koji and others, 2023, McDonald and others, 2023, Yukihiro and others, 2023). However, most libraries are open-source projects, and given the small community, many libraries are no longer being actively maintained.

Over-the-air Programming

The high-level languages described so far have varying support for over-the-air updates, mostly in the form of remote REPLs. However, the idea of updating low-end embedded devices over-the-air is not new, and the idea has received considerable attention in the context of sensor networks. For instance, already in 2002 Levis and Culler (2002) created a byte-code interpreter for tiny microcontrollers called Maté. Maté was designed to reprogram sensor networks through self-replicating packages of just 24 instructions. More recently, Baccelli et al. (2018) looked at reprogramming low-end devices with a low-code approach, where Business Process Modelling Notation (BPMN) (Rospocher et al., 2014) is translated into JavaScript code by a central server and sent to the devices of the sensor network over the air. Similar to a lot of systems for over-the-air updates, in this work the software running on the low-end device is updated in its entirety. The functional approach was also explored by Lubbers et al. (2021) in the Clean language (Brus et al.,

1987), specifically, task oriented programming was adopted for tiny low-end microcontrollers. Task oriented programming is a programming paradigm for distributed systems, where tasks represent units of computations, which—like monads—can be constructed with combinators, and which share data via their observable values (Plasmeijer et al., 2012). Individual tasks can be compiled to bytecode and sent to devices to be executed, enabling partial updates of the code. While these three approaches are very different, each focuses on low-end microcontrollers similar to WARDuino. By contrast de Troyer et al. (2018), developed a reactive programming approach for the more powerful Raspberry Pi computers. Raspberry Pi’s are far bigger than the low-end devices targeted by WARDuino, and have subsequently much more resources, but they are still used considerably for the Internet of Things (Maksimovic et al., 2014). The reactive language allows the entire life-cycle of a device to be programmed, including the deployment of software and over-the-air updates. Again, the over-the-air updates are limited to the entire program.

In contrast to these works, the main motivation behind WARDuino is to simplify development of IoT applications in a way that is widely applicable. In this spirit, the idea of over-the-air updates is adopted by WARDuino as an extension to the classic debugging operations. This provides developers with powerful operations during debugging; partial code updates, and changing variable values. Additionally, we believe the small-step semantics of the over-the-air updates present a novel contribution, which in future work can form the basis for proving the correctness of updates by showing that programs remain well-typed.

While we are not aware of any other attempts to describe over-the-air updates of binary code through a small-step semantic, there is some theoretical work on live updates. For instance, in 1996, Gupta et al. (1996) showed that the validity of live updates is generally undecidable. However, most work has been focused on distributed systems specifically, and the issues that arise due to the distribution of nodes. identified the important problem of; when is a system in the appropriate state for a live update? The proposed solution was later improved by Vandewoude et al. (2007). In WARDuino this problem is largely circumvented because the updates are integrated in the debugger.

WebAssembly on Embedded Devices

Since the start of the WARDuino project, many others have started looking into running WebAssembly on embedded devices. These projects range widely in scope and focus. Here, we give an overview of some projects bringing WebAssembly to IoT and Edge Computing.

The WebAssembly Micro Runtime (Huang and Wang Xin, 2021) and WASM3 (Massey and Shymanskyy, 2021) are WebAssembly runtimes with a small memory footprint like WARDuino. The WebAssembly Micro Runtime specifically aims to have a tiny memory footprint such that it can be used in constraint environments, such as small embedded devices. The runtime largely supports the WASI standard (Hickey et al., 2020), including the `pthreads` API that allows developers to use multithreading. However, it does not support the WASI `sockets` API providing internet connection. WASM3 can run on microcontroller platforms, such as the ESP32. In the first place, the microcontroller support is a research project to test and showcase their novel interpreter that uses heavy tail-call optimizations rather than JIT compilation to improve performance (Massey and Shymanskyy, 2022). Not using JIT compilation is the main reason the WASM3 interpreter has such a small footprint and can run on microcontrollers. WASM3 supports most of the new WebAssembly proposals and can run many WASI apps, but it does not fully support the `pthreads` or `sockets` API. WARDuino brings a more general mechanism to WebAssembly that allows both synchronous and asynchronous network communication without the need for a full-fledged operating system. Unlike the WebAssembly Micro Runtime, WASM3 has explored remote debugging. Specifically, the project examined the remote debugging protocol of GDB to try and debug source-level WebAssembly (Shymanskyy, 2023). This effort was not targeted at microcontrollers, but could work on embedded devices with a JTAG hardware debugger. By contrast, WARDuino can remotely debug microcontrollers without the need for a dedicated hardware debugger. Additionally, WARDuino supports over-the-air updates, something neither the WebAssembly Micro Runtime nor WASM3 allow.

Wasmer (Wasmer, Inc., 2022) is another WebAssembly runtime that reports to be fast and small enough to run on Cloud, Edge and IoT devices. The runtime supports WASI programs, but it does not support threading and is waiting for the official Threads Proposal for WebAssembly to reach the implementation phase, which it has not at the time of writing. However, it does support Emscripten's `pthread` API. Unfortunately, the project does not provide a list of supported microcontroller platforms and does not seem to target devices with limited memory. Neither does the project provide clear instructions on how to execute the Wasmer runtime on embedded devices. While the project developed their own WebAssembly package manager (`wapm`), there are currently no packages for IoT protocols such as MQTT, or for interacting with hardware peripherals. Wasmer is currently working on its debugging support, which is limited at the time of writing. Moreover, the project does not seem to target remote debugging of embedded devices at this stage.

Interrupt Handling in WebAssembly

There are different efforts in the WebAssembly community to add support for handling asynchronous to the standard. As WebAssembly is still primarily used on the web, most of the new proposals to the standard are made because of certain needs arising from the web. When writing this chapter originally in 2022, the proposals under consideration, were the threads and stack switching proposals (WebAssembly Community Group, 2022). In 2024, the threads proposal reached the second to last phase of the WebAssembly standardization process, “*Phase 4 - Standardize the Feature*”.

The threads and stack switching proposals allow WebAssembly to run asynchronous code, this could then be used to add interrupts to WebAssembly. These proposals themselves do not provide a dedicated system for interrupts. Developers would have to implement a complete callback handling system in WebAssembly themselves. Without a dedicated system for interrupts, everything would have to be implemented directly into WebAssembly, which is not a trivial task. Additionally, both proposals allow the space taken by the stack(s) to grow fast, an unwanted side effect on memory constrained devices. WARDUino only executes one callback at a time keeping the stack size as low as possible.

A recent chapter by Phipps-Costin et al. (2023), alternatively proposes a universal target for non-local control flow that relies on effect handlers (Plotkin and Pretnar, 2009). In our opinion this solution is more attractive than the threads and stack switching proposal, primarily due to its simplicity—it only adds three new instructions—and its universality. Similar to the stack switching proposal, a callback handling system comparable to the one described here, could most likely be built on top of this system. However, continuations are still expensive, since they also need to save the entire stack. Furthermore, the proposal is again not enough to support asynchronous primitives. The effect handlers would only allow us to create a system for handling interrupts with callback functions, directly in WebAssembly code. In this case, we arrive at the same solution we have outlined in this chapter, except the implementation has moved from the virtual machine to WebAssembly code. It is not clear whether this approach would have any benefits.

The WebAssembly System Interface (WASI) (Hickey et al., 2020) is a collection of standardized APIs for system level interfaces. It is not part of the official WebAssembly standard, but is widely used. When developing our callback system, WASI had partial support for the *pthreads* API. In recent years, WASI has started to developed their uniform architecture for interoperable interactions with the host environment, called the *component model* (“WebAssembly/Component-Model,” 2025). As part of the component model, WASI is working on a new async proposal that goes beyond our

callback system, and aims to add native support for asynchronous functions to the component model. We conjecture that this proposal could be used to implement a callback handling system similar to the one we have described in this chapter. However, at the time of writing, the proposal is still being actively developed for the next major version of the component model. Building a callback handling system on top of WASI has its own challenges, but using it on embedded systems adds an additional layer of constraints. As a start, simply supporting the full WASI specification on embedded devices has proven to be complicated in practice (Massey and Shymanskyy, 2021).

3.12 Conclusion

This chapter presents the design and implementation of WARDuino that addresses key challenges associated with developing IoT applications: *low-level coding, portability, slow development cycle, debuggability, hardware limitations, and bare-metal execution environment*. The WARDuino virtual machine enables programmers to develop IoT applications for microcontrollers in high-level languages—compiled to WebAssembly—rather than low-level languages such as C. Higher-level languages can help developers by providing automatic memory management and by giving extra guarantees via type systems. Additionally, using a universal compile-target such as WebAssembly, WARDuino can greatly improve the *portability* of microcontroller programs. The virtual machine supports the WebAssembly core specification and several important extensions to support common aspects of IoT applications.

Access to device peripherals and common M2M protocols is provided by WebAssembly primitives embedded in the virtual machine. These primitives include functions for synchronous (HTTP) and asynchronous (MQTT) communication protocols. To support asynchronous code, WARDuino allows developers to assign callback functions as handlers for asynchronous events, such as incoming MQTT messages or button presses. Whenever a subscribed event occurs, WARDuino will transparently execute the callbacks in isolation of the running program as shown by the small step reduction rules for the callback handling system.

Language integration for high-level languages, exposes the WARDuino primitives as a library with an interface that is conventional for the host language. We have presented different levels of integration for the AssemblyScript language, with higher integration bringing more of the advantages of high-level coding to WARDuino. Our AssemblyScript library, for example, exposes primitives that accept strings although WebAssembly does not have a *string* type. Internally, our library translates the AssemblyScript strings to

WebAssembly memory slices. Developers can thus use WARDuino without having to worry about these kinds of implementation details, or deal with the headaches of *low-level coding*.

Another important contribution is the improved *debuggability* of microcontrollers provided by the WARDuino remote debugger. Developers can send debug messages over any communication channel to the virtual machine and mandate it to pause, resume, step or dump its state. In the paused state, developers can use the same mechanism to reprogram a running application. WARDuino can update local variables, functions, and even the entire program over the air. This speeds up the *slow development cycle*, as developers no longer need to wait while their program is re-flashed to the device. To further ease debugging we created a VSCode plugin that allows remote debugging of a WARDuino instance in a graphical user interface. Thereby, creating a development experience which is much closer to conventional computer programming.

Uniquely, the debugging, over-the-air programming, and callback handling system have been described formally as extensions to the operational semantics of WebAssembly. The small-step reduction rules provide a precise description of these systems, and allow them to be easily implemented by other WebAssembly virtual machines. Furthermore, the semantics allow us to prove desirable properties over the debugger and callback handling system. We prove that the debugging semantics are observationally equivalent to the underlying WebAssembly semantics. In future work, we want to explore other desirable properties, for example that the over-the-air updates cannot break a well-typed WebAssembly program.

We evaluate our work by demonstrating that it is suitable and stable enough to program traditional long-running IoT applications with a smart lamp application in AssemblyScript, a snake game and a whole suite of microbenchmarks. Additionally, we compare WARDuino's performance to that of WASM3 and Espruino. We conclude that we are on average 428 times slower than a native C implementation of computationally intensive microbenchmark. By comparison, WASM3 is 10 times slower and Espruino is 4.991 times slower. Although performance improvements are likely possible, we believe that WARDuino is fast enough for IoT applications as the much slower Espruino is widely and successfully used for this goal.

Chapter 4

Stateful Out-of-place debugging

Some problems are better evaded than solved.

— Tony Hoare

Today, remote debuggers—like the one presented in the previous chapter—are commonly used to debug microcontrollers, however, there are severe disadvantages. Luckily, a novel technique, called out-of-place debugging, can be adopted to largely evade these disadvantages by moving the debugging session to another more powerful device.

During the writing of this dissertation we explored two new concepts for out-of-place debugging, which are essential for microcontrollers. Initially, we explored how to support event-driven applications, which are common in microcontrollers. This lead to an early publication at MPLR 2022 (Lauwaerts et al., 2022). Subsequently, we explored how to support stateful actions on non-transferable resources, such as memory-mapped I/O devices. As part of this work, we developed the first formal model for out-of-place debugging, and proved its soundness and completeness.

4.1 Introduction

Remote debuggers are commonly used to debug various kinds of applications (Högl and Rath, 2006, Li et al., 2009), such as real-time systems (Skvařic Böžić et al., 2024), containerized applications for edge computing (Ozcan et al., 2019), and Internet of Things applications (Lauwaerts et al., 2024, Pötsch et al., 2017). Yet, remote debuggers suffer from three severe disadvantages. Firstly, the debugger is run on the remote device. In the context of constrained devices, this additionally limits the resources available to the debugger. Secondly, the communication channel can be slow, and can introduce latency in the debugging process. Thirdly, the delays introduced by the remote communication can exacerbate debugging interference, also known as the probe effect (Gait, 1986).

These problems can be addressed using out-of-place debugging. It combines local online and remote online debugging, reducing communication latency and overcoming the resource constraints of the remote device. However,

out-of-place debugging is a very new idea, and there are still several open questions and challenges that come with the technique, that have not been addressed yet. Additionally, the technique is without formal foundations. In this chapter, we present the first formalisation of the technique, and attempt to address some important gaps in the existing literature.

Naturally, our work builds on the preceding out-of-place debugging works, and these deserve a proper introduction. Therefore, we first provide an overview of how out-of-place debugging works, and discuss how our contributions relate to previous work.

4.1.1 The origin of out-of-place debugging

Out-of-place debugging was originally devised to minimize debugging interference of remote debuggers for big data applications (Marra et al., 2018), by moving the debugging session to another device. The first out-of-place debugger, IDRA, was developed for the Pharo language, and allowed for debugging of live distributed big data applications. By moving the debugging session out of place, IDRA could debug a node in the network without affecting the live execution of the distributed software. The prototype showed how out-of-place debugging can reduce the debugging latency significantly in the context of large clusters.

4.1.2 Out-of-place debugging for microcontrollers

In the context of embedded applications, out-of-place debugging has great potential for improving the debugging experience offered by remote debuggers, by freeing the debugger from much of the limitations of constrained devices.

An initial investigation by Rojas Castillo et al. (2021) looked at out-of-place debugging as a solution for live debugging of *in-production* embedded applications. The work paved the way for using out-of-place debugging on microcontrollers, and while its topic is very interesting, there are many questions around the idea of debugging in production. In-production debugging is rarely seen in practice, and considered by some to be undesirable. Regardless, out-of-place debugging can provide numerous other benefits to debuggers for microcontrollers. In this dissertation, we will therefore not concern ourselves with the problem of in-production debugging, and instead present how we adapted—and extended—out-of-place debugging to work for microcontrollers during the traditional development stage.

4.1.3 The gaps in out-of-place debugging

Since out-of-place debugging is still a very young technique, it is not surprising that there are some important gaps in the existing work around it. There are three important gaps that we attempt to fill in this chapter. While these gaps are not specific to microcontrollers, they are especially relevant in this context.

First, out-of-place debugging currently lacks a sound formal foundation. We therefore developed the first formalisation of the technique based on WebAssembly. However, our formalisation illustrates and captures the essence of out-of-place debugging without many WebAssembly specifics—and so we argue, is more broadly applicable.

Second, existing work fails to address possible state desynchronization between the remote and local device. Existing solutions typically limit internal state changes to the local debugging environment, making it difficult to debug essential operations like MQTT communication in Internet of Things systems. In our formalisation, we show how to handle stateful operations on non-transferable resources through limited synchronization of the state between the local and remote devices.

Third, non-transferable resources are only accessed in a synchronous request-driven way. The client debugger will request information about non-transferable resources from the server, and *pull*, or *transfer*, the information to the local client session. However, some non-transferable resources may act in an asynchronous way, *pushing* information at arbitrary times. To solve this, we extend out-of-place debugging to support *event-driven* access to non-transferable resources, alongside the typical *request-driven* access.

In the original publication (Lauwaerts et al., 2022), we used the terms *pull* and *push*, here we use *request-driven* and *event-driven* instead.

4.2 Background: Out-of-place debugging

Before delving into the details of our contributions, we first provide an overview of how out-of-place debugging works, and discuss the general out-of-place debugger architecture. Out-of-place debugging provides the debugging experience of a remote debugger, while running most of the code on a local device, thereby reducing debugging latency and interference. It allows for debugging live applications, as the debugging session is isolated from the live execution of the program. Additionally, by running the debugging session out-of-place, the debugger can have access to more computational power and memory, or other resources, enabling more complex debugging techniques. We will illustrate the various concepts involved using our prototype implementation build on top of the WARDuino (Lauwaerts et al., 2024) virtual machine.

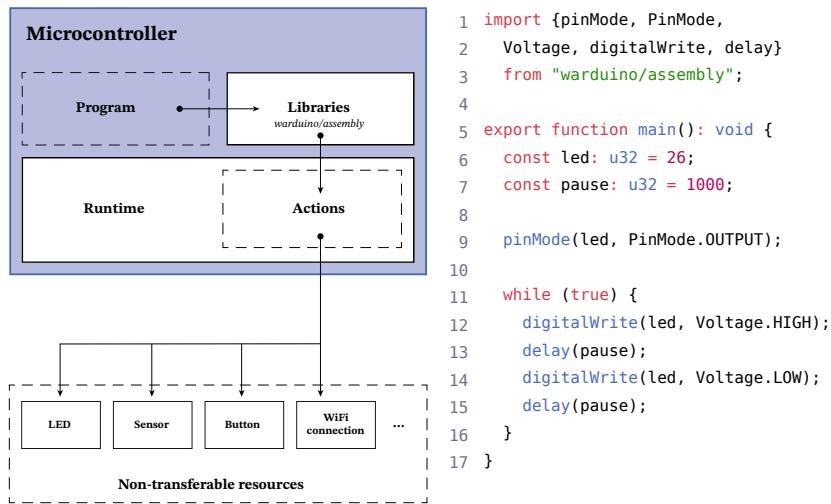


Figure 4-1. Typical blinking LED program for microcontrollers, illustrating non-transferable resources in out-of-place debugging. *Left:* A schematic of the microcontroller. *Right:* The AssemblyScript code for the program.

4.2.1 Example: a blinking LED

Figure 4-1 shows the typical blinking LED example for microcontrollers in AssemblyScript. The application uses the WARDUINO actions, imported on the first line of the program. After the correct mode for the LED’s pin has been set, the program will turn it on and off in an infinite loop with a small delay. The left side of the figure shows a schematic representing the setup of the microcontroller. The AssemblyScript program is compiled to WebAssembly and run on the microcontroller using a WebAssembly runtime. The runtime provides a series of functions to access the non-transferable resources of the microcontroller, such as the LED, buttons, and sensors—we call these functions *actions*.

4.2.2 Debugging with Out-of-place debugging

A developer can use an out-of-place debugger to debug the example application locally on their own machine, while still maintaining the effects on the remote microcontroller, in this case the LED can still turn on or off. Often microcontrollers do not have enough memory to run an additional debugger alongside the application. By using out-of-place debugging, this is no longer necessary. The microcontroller only needs to run a minimal stub to receive a handful of debugging instructions to instrument the runtime.

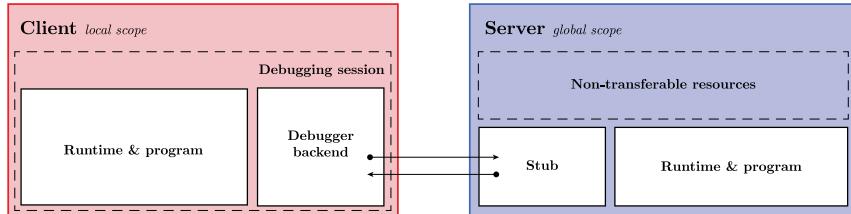


Figure 4-2. Schematic showing the concept of out-of-place debugging with all the involved components.

Figure 4-2 shows the components involved in out-of-place debugging, the developer's local *client* on the left, while the right side shows the remote *server*. The remote server is the device where the software is intended to run. In the case of the blinking light application, this would be the microcontroller that controls the LED. Uniquely in out-of-place debugging, the entire debugging session—consisting of the runtime and the program being debugged—lives on the client.

Note that the server may possess *non-transferable* resources, such as the LED in the example, which cannot be relocated along with the runtime and program to the client. We differentiate between two types of non-transferable resources—based on the way they are accessed or produce information—*synchronous* and *asynchronous*. Synchronous resources, are those accessed by the program synchronously, such as the LED in the example. Asynchronous non-transferable resources on the other hand can produce data at any point in the program, such as hardware interrupts for buttons or motion detectors.

To maintain the benefits of remote debugging, the client does not simulate the non-transferable resources. Instead, the server maintains a small stub which instruments its runtime, and can receive debug instructions from the debugger backend (client). Specifically, the stub supports direct access to synchronous non-transferable resources through remote function calls. For asynchronous non-transferable resources, the stub (server) can send messages to the client through the same connection.

In the case of our example, the only non-transferable resource is the LED light. We consider the action for controlling the LED stateless because it does not change the internal state of the runtime, and does not depend on any internal state other than its own arguments. Such stateless operations can still effect external state. However, since external state is part of the non-transferable resources it only exists on the remote server. As out-of-place debugging still accesses those resources through the server, we assume that their state remains consistent during debugging.

Despite their small size, we refer to the microcontrollers as the *server*, because they serve the requests for information from the local debugger.

Reversible debugging can make external state inconsistent. We address this in Chapter 5.

4.3 Problem statement

Since out-of-place debugging runs a program on a pair of two devices forming a distributed system, executing code can lead to diverging states between the two devices, thereby affecting the proper execution of the program. This can lead to inconsistent, and incorrect observations of the program’s behavior, making it difficult to identify the root cause of a bug. This is even more problematic when part of the program’s execution is asynchronous. To further clarify the problem of state desynchronization, we look at a use case of out-of-place debugging on an Internet of Things application for microcontrollers.

4.3.1 Example: asynchronous logging of a sensor

Consider the previous LED example, in an Internet of Things setting we would like to control the LED through some communication protocol such as MQTT. Figure 4-3 shows how this can be done in AssemblyScript code. The example is written for our WARDUINO virtual machine. The virtual machine provides actions for the typical MQTT operations, such as subscribe, publish, and keep-alive, see Chapter 3 and Appendix D.7.

The code in Figure 4-3 works as follows, at the start of the program the necessary MQTT configuration is set up, and the microcontroller connects to the local Wi-Fi network. After the connection is established, the microcontroller subscribes to the topic “SENSOR” and wait for incoming messages. At any point, a message can be received on the topic “SENSOR”, at which point the virtual machine schedules the callback function and log the sensor value. On the right-hand side of Figure 4-3, we show a schematic of the microcontroller connected to the MQTT broker. The connection with the MQTT broker is an example of an asynchronous non-transferable resource, which can produce new MQTT messages at any point in the program, and subsequently triggering a callback, such as the *log* function in the example.

4.3.2 Out-of-place debugging for event-driven applications

Previous out-of-place debuggers (Marra et al., 2018, Rojas Castillo et al., 2021), did not support asynchronous non-transferable resources, such as the MQTT connection in the example. Access to non-transferable resources from the client was only possible by request of the server, such as through synchronous remote function calls in the case of Rojas Castillo et al. (2021). This already allowed for continual synchronous polling of a sensor value.

However, such a *request-driven* strategy to access sensor data is often too resource-intensive for embedded applications, and so does not capture all use cases for debugging Internet of Things devices. Many of the peripheral

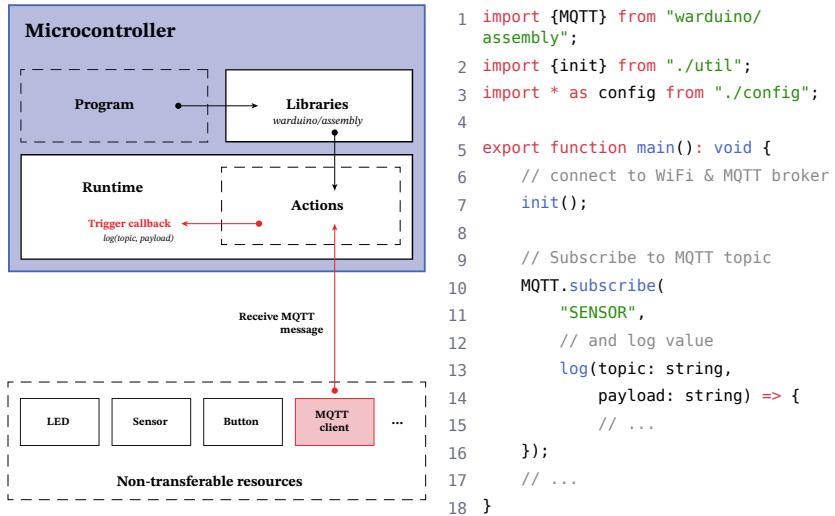


Figure 4-3. Small example application illustrating the state desynchronization problem in out-of-place debugging, when receiving MQTT messages. The application simply logs sensor values received via MQTT messages.

devices attached to a microcontroller use an interrupt-driven interface instead. Such interrupts are generated when certain external events happen, for example when an input-pin changes from low to high. This prevents microcontrollers from having to poll the state of the pin constantly, and save resources by only reacting to changes in the environment when they occur.

4.3.3 Out-of-place debugging for stateful resources

Unfortunately in out-of-place debugging, since the entire debugging session is moved to the local machine, the scheduling of the callbacks happens on the local client, while subscribing callbacks on MQTT topics, and receiving the messages happens on the server. This presents two types of state desynchronization from the perspective of the client, *synchronous* and *asynchronous*.

4.3.3.1 State Desynchronization between two Devices

Harmful synchronous state desynchronization can occur whenever the client instructs the server to execute a piece of code. This code can potentially change the memory state on the server leading to state desynchronization. This is especially problematic when these state changes are needed for the

program to continue running. In such cases, the server will use outdated values from memory instead of the updated values from the client.

While synchronous state desynchronization is triggered by the server and happens at specific, well-defined moments, asynchronous desynchronization can occur at any time. Relevant state on the client can change asynchronously, outside of the local context of the debugger. These changes are caused by asynchronous events which can occur at any time in the program, such as receiving MQTT messages.

The example in Figure 4-3, illustrates both synchronous and asynchronous state desynchronization. First, the `MQTT.subscribe` function, illustrates synchronous state desynchronization. It modifies the internal state of the runtime on the server by storing the callback to be triggered upon receiving the “SENSOR” messages, which the subsequent out-of-place code depends on. Second, whenever an MQTT message is received, this message is stored in memory (on the server) and should be executed as soon as the currently executing instruction is finished.

4.3.4 The abstract model of out-of-place debugging

The concept of out-of-place debugging still lacks a sound formal foundation, that captures the entire spectrum of its implementations. Furthermore, the existing work fails to address the full range of side effects of executing code involving non-transferable resources, and how it can lead to *state desynchronization* between the local and remote device. Existing solutions typically limit internal state changes to the local debugging environment, making it difficult to debug essential operations like MQTT communication in Internet of Things (Internet of Things) systems.

Many non-transferable resources feature stateful operations, which can impact a program’s behavior. Without those changes being reflected on the local server, the debugger can never provide an accurate representation of the program’s execution. In scenarios where asynchronous events or interactions with external systems occur (for example receiving an MQTT message), desynchronization of the program state between the two devices can occur at any point in the program’s execution. Traditional methods that strictly scope side effects to the local server fail to account for the dynamic nature of state changes occurring on remote devices.

This chapter introduces stateful out-of-place debugging that bridges the gap between local and remote debugging paradigms more completely. Our method ensures that while the majority of the debugging code executes locally, stateful operations on the remote device are consistently managed and reflected on the local device. In our solution we adopt a minimal syn-

chronization strategy, where synchronous operations transfer the minimal state required for their execution at the point they are invoked. Asynchronous resources send their changes to the internal state to the debugging session as soon as they become available, providing a debugging experience where debugger interference is minimized.

In order for this synchronization to work, our solution identifies the specific requirements non-transferable resources and their operations must satisfy. We demonstrate that meeting these requirements is not very restrictive and show how real-world examples can be implemented using our approach. We further provide proofs that this approach is sound and complete.

4.4 Stateful out-of-place Debugging for WebAssembly

In this section, we present the semantics of out-of-place debugging for WebAssembly. In order to have sound and complete semantics, we need to make two key assumptions about the stateful operations in the system. These assumptions are not specific for WebAssembly and can be ensured for a wide range of stateful operations expressed in any programming language:

1. **Statically known state dependency.** Given the argument values for any *synchronous* stateful operation in the system, it must be possible to define a function which identifies all parts of the internal state that the operation depends on, and the state that the operation changes.
2. **Instantaneous partially ordered events.** We assume that for all *asynchronous* non-transferable operations during a debugging session, there exists a *partial* order over the asynchronous events they produce. In addition we assume that events do not have real-time dependencies.

Without the first requirement we would have to rely on possibly time consuming static analysis or conservatively copy the whole state, defeating many of the advantages of out-of-place debugging. This requirement does exclude certain complex operations, where changes to the state are calculated based on some implicit state. However, we believe that for most of such operations the implicit state can be made explicit by passing it to the stateful operation as an argument.

Without the second requirement, the debugger cannot know which of the received events can be (safely) handled next. In this chapter, we focus solely on the order in which they are processed. Other considerations around the exact timing of the events are important for real-time systems, but are impossible to handle in an online debugger context where execution can be paused for arbitrary periods. Although these requirements impose some limitations

WebAssembly syntax

$$\begin{array}{ll} \text{(WebAssembly program state)} K ::= \{s, v^*, e^*\} \\ \text{(Global store)} s ::= \{\text{inst inst}^*, \text{tab tabinst}^*, \text{mem meminst}^*\} \end{array}$$

WebAssembly evaluation

$$\boxed{\{s, v^*, e^*\} \hookrightarrow_i \{s', v'^*, e'^*\}}$$

$$\frac{\{s, v^*, e^*\} \hookrightarrow_i \{s', v'^*, e'^*\}}{\{s, v^*, L^k[e^*]\} \hookrightarrow_i \{s', v'^*, L^k[e'^*]\}} \text{ LABEL}$$

Figure 4-4. The configuration for WebAssembly with embedded actions, supporting transfer and syncing of state based on the semantics of the original paper (Haas et al., 2017).

on the types of stateful operations we can support, we believe that a broad range of stateful operations align with these assumptions.

4.4.1 WebAssembly language semantics

We briefly discussed WebAssembly, and its semantics in the previous chapter (Chapter 3) and we provide a larger overview of the relevant rules from the original paper (Haas et al., 2017) in Appendix C. Here we reiterate the most important aspects of the WebAssembly semantics that are relevant to our formalization of stateful out-of-place debugging.

Figure 4-4 shows the most important syntax rules for WebAssembly. The WebAssembly semantics are grounded in a stack-based virtual machine, where instructions and values operate on a single stack with strict typing to guarantee fast static validation. Again, we base our formalization on the semantics from the original WebAssembly paper by Haas et al. (2017), where the core semantics include structured control flow (blocks, loops, and conditionals) and memory management via linear memory. Important here is WebAssembly’s intentional exclusion of external interface definitions, including I/O operations. This design choice enables us to deliberately sculpt the I/O operations for our synchronization system, as we will show in Section 4.4.2.

The execution of a WebAssembly program is defined by a small-step reduction relation, denoted as \hookrightarrow_i where, i refers to the index of the currently executing module. The relation \hookrightarrow_i is defined over a configuration $K = \{s; v^*; e^*\}$, with global store s , local values v^* , and the current stack of instructions e^* . Important for our semantics, the global store s contains instances

New WebAssembly syntax

(Global store)	$s ::= \{inst\ inst^*, tab\ tabinst^*, mem\ meminst^*, act\ A\}$
(Action table)	$A ::= a^*$
(Action)	$a ::= \{\text{code}\ cl, \text{transfer}\ t, \text{transfer}^{-1}\ r\}$
(Backward transfer)	$t ::= (v^* \times s \rightarrow s', \text{where } s' \subseteq s)$
(Forward transfer)	$r ::= (s \rightarrow s', \text{where } s' \subseteq s)$

Figure 4-5. The configuration for WebAssembly with embedded actions, supporting transfer and syncing of state based on the semantics of the original paper (Haas et al., 2017).

of modules, tables, and memories. The global store allows access to any function within a module instance, denoted as $s_{\text{func}}(i, j)$, where i represents the module index and j corresponds to the function index.

The WebAssembly semantics makes use of administrative operators to deal with control constructs, for example $\text{call } i$ denotes a call to a function with index i . To mark the extend of an active control struct, expressions are wrapped into labels. Evaluation context L^k are used in the *Label* rule to unravel the nesting of k labels, allowing to focuses on the currently evaluation expressions e^* . This rule, as defined in the WebAssembly semantics, is important for defining the out-of-place debugger semantics because it allows capturing the current continuation, (i.e. $L^k[]$), just before invoking a remote call.

4.4.2 Extending WebAssembly with Embedded Actions

In Chapter 3, we discussed in great detail how WARDuino extends WebAssembly with actions for peripherals of constrained devices, and other resources specific to embedded and Internet-of-Things applications. For the purposes of the out-of-place debugger, these actions correspond precisely with the synchronous accesses of non-transferable resources. In Chapter 3, actions did not differ from other WebAssembly functions, but in the context of out-of-place debugging we need to distinguish between the two, and extend actions with two transfer functions to enable our sparse synchronization strategy.

New WebAssembly evaluation

$$\boxed{\{s, v^*, e^*\} \hookrightarrow_i \{s', v'^*, e'^*\}}$$

$$\frac{s_{\text{func}}(i, j) \neq \text{cl} \quad s_{\text{act}}(j) = a \quad \{s, v^*, \text{call } a_{\text{code}}\} \hookrightarrow_i^* \{s', v'^*, v\}}{\{s, v^*, \text{call } j\} \hookrightarrow_i \{s, v^*, v\}}$$

Figure 4-6. The semantics of actions, and invoking instructions in WebAssembly.

We have extended WebAssembly with a set of non-transferable actions which are clearly separated from regular code execution. This design choice enables us to have a clear and easy division between transferable and non-transferable code. Figure 4-5 shows the extended WebAssembly syntax rules for non-transferable resources support. The changes are highlighted.

The WebAssembly global store is extended with a *global* action table A containing all actions, each action a is a named pair of a closure cl and a transfer functions t and r . The closure consists of the code which performs the action over the non-transferable resource. The backward transfer function t , returns the state s' needed to perform the action, given the arguments v^* and the current state s of the server. The forward transfer function r , produces the state s' that has been altered by executing the action given the state s after executing the action on the client. We refer to elements of named tuples, such as the transfer function as a_{transfer} , or the action table s_{act} .

Naturally, the semantics of actions needs to be define both for when the debugger is active and during normal execution. Figure 4-6 shows how actions are executed during normal execution. Whenever a function is called that is not present in the current instance i , the action rule finds the closure in the action table and shifts execution to evaluating the closure. This is similar to how the WebAssembly semantics handles function calls. Important to note is that actions are atomic, and reduce to a single value in one step, $\{s; v^*; \text{call } a_{\text{code}}\} \hookrightarrow_i^* \{s'; v'^*; v\}$. While we could relax this condition for synchronous events, the semantics to support asynchronous events would become more complex as shown in Section 4.5. In the next section we give an overview of the semantics of actions during debugging.

4.4.3 Configuration of the Stateful Out-of-place Debugger

Out-of-place debugging distributes a single program over two distributed entities, the local debugger which acts as the *client*, and the remote microcontroller which acts as the *server*. Recall that the idea is to execute most of the program on the client and only execute code attached to non-transferable

Global syntax rules(Global configuration) $D ::= (S \mid C)$ *Client syntax rules*

(Client configuration) $S ::= \text{es}, m_{\text{in}} ; K ; m$
 (Execution state) $\text{es} ::= \text{running} \mid \text{halted} \mid \text{invoked}(es)$
 (Debug commands) $m ::= \text{play} \mid \text{pause} \mid \text{step}$
 (Internal messages) $m_{\text{in}} ::= \emptyset \mid \text{sync}(s, v)$

Server syntax rules

(Server configuration) $C ::= \overline{\text{es}}, \overline{m_{\text{in}}} ; K$
 (Execution state) $\overline{\text{es}} ::= \text{running} \mid \text{halted}$
 (Internal messages) $\overline{m_{\text{in}}} ::= \emptyset \mid \text{invoke}(s, e^*)$

Figure 4-7. The syntax rules for a stateful out-of-place debugger, on top of the WebAssembly semantics shown in Figure 4-5. The rules are split into three groups, the global rules, the client rules, and the server rules. Elements in the server configuration are overlined whenever they need to be differentiated from the client configuration.

resources on the server. We define the configuration for stateful out-of-place debugging in Figure 4-7.

The debugger configuration D is split into the client and server sides, $(C \mid S)$, which each hold a WebAssembly configuration K —the program state. The client side represents the main component of the debugger, which is responsible for receiving debug commands from the debugger’s user interface. The server side represents only a small stub running on the remote microcontroller, which must facilitate access to non-transferable resources.

The client syntax rules shown in Figure 4-7, divide the configuration into three main parts divided by a semi-colon. The first component is the internal debugger state, consisting of the execution state es , and the internal message box m_{in} which receive messages from the server. Execution state es can be either *running*, *halted*, or *invoked*. The last state is used to indicate that the client is currently executing a remote invocation, and keeps track of the state of the execution state before the invocation. There is only one possible internal message that can be received from the server, *sync*, which is used to synchronize the state of the client after a remote function invocation. The second component is the WebAssembly configuration K , and the third component is the external-facing message box m for debug commands received

from the user interface. For brevity, we have limited the supported debug commands to *play*, *pause*, and *step*.

The server configuration consists of the two components; the internal debugger state and the WebAssembly program state K . The internal debugger state contains the execution state \bar{e}_S , and the internal message box \bar{m}_{in} , which receives messages from the client. The server can receive just one internal message, *invoke*, which is used to invoke an action. In order for the right state to be synchronized, the messages passes along the WebAssembly global store s and list of instructions e^* . We go into more details when discussing the evaluation rules. For clarity, we place a line over these components to differentiate them from the similar components in the client configuration.

Breakpoints
can be added
to the semantics,
analogous
to the ap-
proach in
Chapter 3.

In our implementation we also have an outgoing message box used to communicate all the information needed to update the debugger frontend, in order not to clutter the semantics we omit this message box in the semantics.

4.4.4 Stepping in a Stateful Out-of-place Debugger

Given the syntax rules for the out-of-place debugger, we can now define the evaluation rules, which are of the form $(C \mid S) \xleftrightarrow{d,i}^* (C' \mid S')$. Figure 4-8 shows the rules for the client side of the out-of-place debugger. The debugger message box m in C receives debug messages from the debugger frontend, which are processed in the order they are received in. Conceptually, step operations may involve either the server or the client taking a step. The determining factor is whether the step requires access to a non-transferable resource. Below, we outline the step and run rules.

step-client When the client is halted, and receives the debug command *step* in the external-facing message box, and the next instruction is not an action, then the execution takes a single step in the underlying WebAssembly semantics from K to K' .

play Whenever the halted server receives a *play* message, it will move the server to the *running* state.

pause Whenever the running server receives a *pause* message, it will move the server separator to the *halted* state.

run-client Similarly, when the server can take a (local) step in the underlying semantics, and is in the *running* state, the server takes a step through the underlying semantics.

These rules allow the debugger to execute a WebAssembly program that does not contain any actions. When during the execution of the program an action is encountered execution needs to be transferred to the server. For fullness,

Client evaluation rules

$$\begin{array}{c}
 \frac{\neg(K = \{s; v^*; L^k[\text{call } i]\} \wedge a = A(i)) \quad K \hookrightarrow_i K'}{(\text{halted}, \emptyset ; K ; \text{step} | S) \hookrightarrow_{d,i} (\text{halted}, \emptyset ; K' ; \emptyset | S)} \text{step-client} \\
 \\
 \frac{}{(\text{play}, \text{bp}, (\text{halted}, \emptyset ; K ; \text{play}) | S) \hookrightarrow_{d,i} ((\text{running}, \emptyset, K) | S)} \text{play} \\
 \\
 \frac{}{(\text{pause}, \text{bp}, (\text{running}, \emptyset, K) | S) \hookrightarrow_{d,i} ((\text{halted}, \emptyset ; K) | S)} \text{pause} \\
 \\
 \frac{\neg(K = \{s; v^*; L^k[\text{call } i]\} \wedge a = A(i)) \quad K \hookrightarrow_i K'}{((\text{running}, \emptyset, K | S) \hookrightarrow_{d,i} (\text{running}, \emptyset, K' | S))} \text{run-client} \\
 \\
 \frac{K = \{s; v^*; L^k[v^n \text{ call } i]\} \quad a = A(i) \quad a_{\text{transfer}(v^n, s)} = s'}{(\text{halted}, \emptyset ; K ; \text{step} | \text{halted}, \emptyset ; K^c) \hookrightarrow_{d,i} (\text{invoked(halted}), \emptyset, K ; \emptyset | \text{halted}, \text{invoke}(s', v^n \text{ call } i) ; K^c)} \text{step-transfer} \\
 \\
 \frac{K = \{s; v^*; L^k[v^n \text{ call } i]\} \quad a = A(i) \quad a_{\text{transfer}(v^n, s)} = s'}{(\text{halted}, \emptyset ; K ; \text{step} | \text{halted}, \emptyset ; K^c) \hookrightarrow_{d,i} (\text{invoked(running)}, \emptyset, K ; \emptyset | \text{halted}, \text{invoke}(s', v^n \text{ call } i) ; K^c)} \text{run-transfer} \\
 \\
 \frac{K = \{s; v^*; L^k[v^n \text{ call cl}]\} \quad \text{update}(s, \Delta) = s' \quad K' = \{s'; v^*; L^k[v]\}}{(\text{invoked(es)}, \text{sync}(\Delta, v) ; K ; m | S) \hookrightarrow_{d,i} (\text{halted}, \emptyset ; K' | S)} \text{sync}
 \end{array}$$

Figure 4-8. The semantics of remote action invocation in out-of-place debugging.

Figure 4-8 already contains the rule for handling the forward transfer of state by the client—as it is received from the server after a remote action call.

step-transfer When during stepping, the next instruction is a call to an action, the execution is transferred to the server device. The transfer function a_{transfer} calculates the state s' required to execute the action on the client. This state is passed to the server through the *invoke* message, along with the arguments of the call v^n , and the function id i to call.

Note that the client’s execution state transitions to *invoked(halted)*. Before executing code on the server, we must remember that the execution was halted to restore it after the call. This is crucial because execution on the server can be triggered both while the client is halted and while it is running.

run-transfer When the client is in the running state and the next instruction is a call to an action, the execution is transferred to the server device. This rule is entirely analogous to the step-transfer rule, with that

Server evaluation rules

$$\frac{s'' = \text{update}(s, s') \quad \{s''; \varepsilon; v^n \text{ call } i\} \hookrightarrow_i \{s; \varepsilon; v\} \quad \Delta = a_{\text{transfer}^{-1}}(s) \text{ invoke} \\ (\text{invoked}(a), \emptyset ; K \mid \text{halted}, \text{invoke}(s', v^n \text{ call } i) ; \{s; \varepsilon; \varepsilon\}) \\ \hookrightarrow_{d,i} (\text{invoked}(a), \text{sync}(\Delta, v) ; K \mid \text{halted}, \emptyset ; \{s; \varepsilon; \varepsilon\})}{}$$

Figure 4-9. The semantics of out-of-place execution, i.e., on the server, in stateful out-of-place debugging.

difference that the server will transition to the `invoked(running)` state. This is important to be able to restore the running state after the call.

sync The synchronization rule updates the state of the client, with the difference received from the server after an invocation. This is identical to the update in the *invoke-start* rule. Finally, the execution state of the client is restored to es.

Figure 4-9 shows how the *invoke* message is handled by the debugger stub on the server side. The process is split into three parts, (1) the server synchronizes the state based on the backward transfer and prepares the action call, (2) the action is performed, and (3) the changes to the WebAssembly state are transferred back to the client.

invoke When the client receives an *invoke* message, it updates the local state s with the snapshot s' of the *invoke* message. The *update* function simply overrides the current state s with those parts that are present in s' . Subsequently, it executes the action by executing it in the underlying WebAssembly semantics. There is only a single value v left on the stack on the client C . At this point, the client makes use of the $a_{\text{transfer}^{-1}}$ function of the action to compute which state needs to be synchronised. This difference is then transferred back to the server in a *sync* message, along with the return value v of the action.

4.5 Modeling Asynchronous Non-transferable Resources

The semantics so far, allow for the out-of-place debugger to handle programs with synchronous operations that are both stateless and stateful. However, in microcontroller systems, actions can be triggered asynchronously by elements such as sensors, hardware interrupts, and asynchronous communication protocols like MQTT. Pure WebAssembly does not have support for callbacks, therefore we extended the WebAssembly semantics with a

lightweight callback handling system in Chapter 3 (see Section 3.7.2 and Section 3.8.5). We made minor adjustments to the implementation to better align with our stateful out-of-place debugger, but the semantics remain the same.

We can summarize the system as follows. The WARDUINO virtual machine captures all asynchronous events into a universal representation—a topic and payload tuple. Whenever an event arrives in the event queue, the WebAssembly runtime will interrupt the current execution, and invoke the callback function associated with the event topic. Such callbacks cannot have a return type, to ensure that callbacks do not break a well-typed WebAssembly program. However, callbacks can update other internal state, such as global variables, or linear memory. Asynchronous events and callbacks further introduce non-determinism into the WebAssembly languages, which can seriously complicate debugging of programs. However, simplifying debugging of non-deterministic bugs is beyond the scope of this chapter, and is an orthogonal problem to that of state desynchronization in out-of-place debugging. We consider this beyond the scope of this chapter, but tackle the problem in the next chapter (Chapter 5), where we present our new multiverse debugger for I/O operations.

4.6 Debugging Asynchronous Non-transferable Resources

The callback system and the asynchronous non-transferable resources it enables, present a second challenge for handling state desynchronization in out-of-place debugging. Identical to the other parts of the program’s runtime, we wish to have the callback system run on the client. Unfortunately, events are generated on the side of the server. Building on the semantics we discussed so far, we show how out-of-place debuggers can deal with these kind of asynchronous state changes in the following sections.

4.6.1 An Example of Asynchronous Resources

To illustrate the challenges introduced by asynchronous resources to stateful out-of-place debugging, we take another detailed look at our running MQTT example (Figure 4-3). Developers familiar with the MQTT subscribe operation, would expect it to send a message to the MQTT broker, indicating that the client is interested in a specific topic. From that moment on, the broker will forward messages of that topic to the client, where they will be handled by a callback function. To implement this action in our system, we expect it to send the appropriate message to the MQTT broker, and register a callback function for those MQTT message in the runtimes callback handling system.

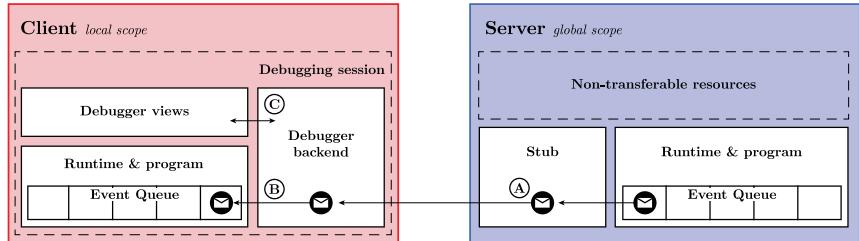


Figure 4-10. The callback system for handling asynchronous events in out-of-place debugging developed as part of our work. The schematic shows how events are forwarded from the server to the client, where they are placed in the WARDuino event queue.

In stateful out-of-place debugging, the update of the callback system by an action is a clear example of synchronous desynchronization, which is handled at the end of the actions invocation. However, whenever the client receives MQTT messages, it places these in the event queue of the callback handling system. This is a clear example of asynchronous desynchronization, which needs to be handled differently.

4.6.2 Accessing event-driven non-transferable resources

In order to support event-driven access to non-transferable resources, the out-of-place debugger hijacks the event system of the virtual machine. Rather than directly executing the callback function whenever an event is received, the event is send from the server to the client, and removed from the event queue in the server.

Figure 4-10 shows a schematic of how the out-of-place debugger handles events in the event system. Whenever a new event arrives in the event queue of the server runtime, it is forwarded via its debugger stub to the client (A). The client stores the forwarded events in a local event queue, mirroring the event queue on the server (B). Events received by the client are not automatically handled. Instead, they are forwarded to the frontend, to be shown in a dedicated view (C). Events will be manually resolved upon the developer's request. When the client receives such a request from the frontend, it will only process the specified event if the partial ordering of events is maintained. This way, the developer can choose at what point in the code an event should be handled, making it easier to reproduce specific situations.

4.6.3 The Callback System in Out-of-place Debugging

We revisit the semantics of stateful out-of-place debugging entirely, since the current semantics have no way of dealing with events produced by non-transferable resources. We will define a new semantics $\hookrightarrow_{d,i}^\alpha$ that encapsulates the previous syntax and evaluation rules, but adds support for synchronization and control of event-driven non-transferable resources.

Our callback system adds two instructions to WebAssembly, which can change the callback map in the global store, *deregister* and *register*. As our example with MQTT subscribe illustrates, actions can use the instructions to change the map on the server. It is crucial to have these changes reflected on the client, since it has sole control of the callback system. However, these changes are still synchronous, so can be dealt with through the invocation rules already presented in Section 4.4.4.

It is important to note, that this synchronization is only necessary from server to client, since control over the callback system lies entirely with the latter. This means, that the server is not able to start a new WebAssembly callback execution autonomously, and therefore does not need its callback map synchronized with any local changes on the client side.

The events are another matter, these are generated asynchronously, and so need to be synchronized asynchronously as well. However, in this case too, synchronization is only necessary from server to client.

4.6.4 Controlling the dispatching of Asynchronous Events

While it is important for microcontroller applications to interrupt a program's execution to handle asynchronous events, during debugging this is extremely distracting and confusing. Debugging relies on giving the developer control over the program's execution, but asynchronous code takes away this control. Furthermore, there are many non-deterministic bugs that depend on a certain order of events, or only appear when events are processed at certain points in the program (Li et al., 2023). We therefore want full control over the impact that asynchronous events have on the control flow of the program.

Figure 4-11 shows the extended semantics of the out-of-place debugger for handling and controlling asynchronous events, defined as the relation $(\hookrightarrow_{d,i}^\alpha)$ which extends $(\hookrightarrow_{d,i})$. To provide developers with control over the event and callback system, the out-of-place debugger disables the automatic dispatching of events, as shown at the top of Figure 4-11. Specifically, the debugger will never take the *interrupt* step. Instead it provides a new debug message *trigger(j)*, which takes the index *j* of a event in the queue to be dispatched. However, some events cannot occur before other events, the most straight-

Adjusted syntax rules

(Debug commands) $m ::= \text{play} \mid \text{pause} \mid \text{step} \mid \text{trigger}(j)$

New valuation rules

$$\boxed{(\hookrightarrow_i) \neq \text{interrupt} \\ \text{dbg} \hookleftarrow_{d,i} \text{dbg}'}$$

$$\frac{\xi = s_{\text{events}(j)} \quad s'_{\text{events}} = \text{remove}(s_{\text{events}}, j) \quad e'^* = \text{construct_call}(s, \xi) \\ K' = \{s', v^*, \text{Clb}[e'^*]e^*\}}{(\text{halted}, \emptyset ; \{s; v^*; e^*\}; \text{trigger}(j) \mid S) \hookleftarrow_{d,i} (\text{halted}, \emptyset ; K' ; \emptyset \mid S)} \text{ trigger}$$

$$\frac{\text{length}(s_{\text{events}}) \leq j \vee \exists \text{ evt} : \text{evt} < s_{\{\text{events}\}}(j)}{(\text{halted}, \emptyset ; \{s; v^*; e^*\}; \text{trigger}(j) \mid S) \hookleftarrow_{d,i} (\text{halted}, \emptyset ; \{s; v^*; e^*\}; \emptyset \mid S)} \text{ trigger-invalid}$$

$$\frac{K'_{\text{events}} \neq \emptyset \quad K''_{\text{events}} = \emptyset \quad s = \{\text{events } K'_{\text{events}}, \text{memory memslice}^*\}}{(\text{es}, \emptyset ; K ; \emptyset \mid \overline{\text{es}}, \emptyset ; K') \hookleftarrow_{d,i} (\text{es}, \text{sync}(s) ; K ; \emptyset \mid \overline{\text{es}'}, \emptyset, K'')} \text{ transfer-events}$$

$$\frac{K = \{s; v^*; e^*\} \quad \text{update}(s, \Delta) = s' \quad K' = \{s'; v^*; e^*\}}{(\text{es}, \text{sync}(\Delta) ; K ; \mid S) \hookleftarrow_{d,i} (Q, \text{bp}, (\text{es}, \emptyset, K') \mid S)} \text{ sync-events}$$

Figure 4-11. The semantics of event-driven asynchronous non-transferable resources in out-of-place debugging $\hookleftarrow_{d,i}^\alpha$, which encapsulates the relation $\hookleftarrow_{d,i}$, and provides control over the non-determinism of events to the developer.

forward case is where one MQTT message is the consequence of another. In such cases, reordering the events may result in execution paths that are impossible without the interference of the debugger. To prevent the debugger from causing such impossible scenarios, the semantics assumes there is a partial order relation $<$ for the events in the queue. At any point in the debugging session, an event can only be dispatched if there is no undispatched event that is smaller under this relation. The *transfer-events* rule describes how the client sends events to the server, as soon as the events are received. Since the event queue is an extension of the WebAssembly state, the same synchronization and updating mechanism is used as before. We provide a summary of each rule below.

trigger When the client receives a trigger message for event at index j , it pops the event from the event queue, and identical to the *interrupt* rule in Figure 3-6 (Section 3.8.5), it calls the corresponding callback function.

trigger-invalid If the index of the event in the trigger message is out of bounds, or the event is invalid, because there are still undispatched events that are smaller under the partial order relation, the server will return an error message.

transfer-events This rule shows how all events arriving on the client are forwarded to the server through the same synchronization message we used before. The message includes the events in the queue, and slices of memory containing the events' topic and payload.

4.7 Correctness of Out-of-place Debugging

Given the presented formalization of stateful out-of-place debugging, we can now proof the soundness and completeness of the approach. Let us first restate our basic assumptions about the semantics of the out-of-place debugger.

Given that we work on a theoretical model of our debugger, we must necessarily make some assumptions about the real-world. Specifically, the influence of events on a program's execution is crucial for our debugger, since the debugger allows developers to control the order in which events are processed. We assume that the behavior of the events can be fully modeled as a partial order, and events can otherwise occur at any point in the program and can follow each other instantaneously. This assumption can be captured by two important axioms.

First, for any program the asynchronous events follow a partial order $<$, known to the debugger. This requirement is essential to ensure that the debugger does not cause impossible execution paths by triggering events in the wrong order.

Axiom 4-1. (Event ordering) Asynchronous events can be ordered using the partial order $<$.

Second, we will assume that events can follow each other instantaneously, and can occur at any point in the program as long as the partial order allows it. This implies that any interleaving of partially ordered events in the program is theoretically possible in the language semantics, and so may be explored by the debugger without breaking any soundness or completeness properties.

Axiom 4-2. (Event interleaving) Under the partial order $<$, any interleaving of events in the program is possible.

While we choose a very simple model of the program-environment interactions here, we believe that the assumptions already capture a large part of

real-world programs. We see no reason, why the simple partial order model cannot be extended to more complex models. We return to this point in Section 4.10 when discussing related work on *environment modeling*. With these basic assumptions in mind, we can examine soundness and completeness for the stateful out-of-place debugger—starting with soundness.

Theorem 4-1. (Debugger soundness) Let $\text{dbg}_{\text{start}}$ be the start debugger configuration with the client containing WebAssembly state K . Let dbg be a debugging configuration with the client containing WebAssembly state K' , and the steps $\hookrightarrow_{d,i}^{\alpha,*}$ the result of a series of debug messages. Then:

$$\forall \text{dbg} : \text{dbg}_{\text{start}} \hookrightarrow_{d,i}^{\alpha,*} \text{dbg} \implies K \hookrightarrow_i^* K'$$

Proof Sketch. The proof proceeds by induction on the steps in the debugging session.

Base case. Only a few cases need to be considered, since all other rules cannot be applied to $\text{dbg}_{\text{start}}$. The following rules do not change the state K in C , *play*, *pause*, *step-client*, *run-client*, and *pass-trigger*. At any point in a debugging session asynchronous events can arrive in the event queue of the server S . This means that the first step can be the *transfer-events* rule, which also does not change the state of K in C .

Inductive case. The following rules do not change the state K in C , *play*, *pause*, *step-client*, *run-client*, *invoke-start*, *invoke-run*, *invoke-end*, *pass-trigger*, *trigger-invalid*, and *transfer-events*. The cases *step-server* and *run-server* simply take a step in the underlying semantics. The interesting cases are, *sync*, *sync-events*, and *trigger*.

1. In case of the *sync* rule, the state K is updated to K' . By Lemma F-1 we know the rule is proceeded by a *step-transfer* or *run-transfer* step. These in turn must be followed by an *invoke* step. By definition of the backward transfer function, we know that the *invoke* has the same effect, leading to K'' . Since the forward transfer transmits all changes back to the client, the updated state after the *sync* rule is equivalent to K'' .
2. In the *sync-events* case, we get the changes from the event queue, which is the same as if the events were dispatched on the server. By Axiom 4-2, any interleaving of events is possible, thereby an analogous path in \hookrightarrow_i must always exist.
3. The *trigger* rule handles the dispatching of events in the exact same manner as if the events were dispatched on the server.

□

Next we consider the completeness of the out-of-place debugger.

Theorem 4-2. (Debugger completeness) Let K be the start WebAssembly configuration for which there exists a series of transitions \hookrightarrow_i^* to another configuration K' . Let $\text{dbg}_{\text{start}}$ be the corresponding starting debugger configuration with K in the client, and dbg the debugging configuration with K' in the client. Then:

$$\forall K' : K \hookrightarrow_i^* K' \implies \text{dbg}_{\text{start}} \hookrightarrow_{d,i}^{\alpha,*} \text{dbg}$$

Proof Sketch. The proof for completeness follows almost directly from the fact that for every transition in the underlying language semantics, the debugger can take a corresponding step. We can construct a sequence of step commands of the exact length as the number of steps in $K \hookrightarrow_i^* K'$. Each step command is handled in one of two ways.

1. *For steps that can be taken out-of-place*, the debugger gets to the same state with the *step-client* rule, which uses the underlying language semantics.
2. *Otherwise*, the debugger uses the invoke mechanism to get an equivalent path. We know the path will use either *step-transfer* or *run-transfer*, followed by *invoke* and *sync*. By definition of the backward and forward transfer functions, this gives the same K' in dbg .

Lastly, at any point in the execution in \hookrightarrow_i , the event queue may not be empty, leading to the *interrupt* rule. During debugging the same can happen on the server S , which leads to the *transfer-events* rule. After the *sync* step, the state K in C is the same as at the start of the *interrupt* rule during normal execution. This means that the same callback can be triggered with the *trigger* rule at the exact same place in the program. \square

Given the proofs of completeness and soundness, we can conclude that the operations of the out-of-place debugger do not interfere with the underlying language semantics. It is important to acknowledge again, that the correctness of the debugger is based on the following assumptions: the underlying language semantics is sound, the control flow of the program is only influenced by the order of events and not their concrete timing, and events can arrive at any time under the given partial order of events.

4.8 Implementation

We have implemented the stateful out-of-place debugger formalized above in a prototype debugger, called *Edward*. The *Edward* debugger is built on

top of the WARDuino runtime (Lauwaerts et al., 2024), a WebAssembly runtime for microcontrollers. The prototype provides the features described in the previous section. Additionally, we created a new high-level interface for defining actions which integrates the state synchronization interface described in Section 4.4. The stateful debugger can be used in VS Code to debug AssemblyScript programs running on an instance of the WARDuino runtime, thanks to a dedicated extension to the VS Code IDE.

4.8.1 Virtual Machine Requirements

In order to implement out-of-place debugging, any candidate VM must support the following:

1. Standard instrumentation required for halting and stepping through a program.
2. Support forward and backward state transfer for non-transferable resources.
3. Update the state provided the data received from the transfer functions.
4. Capture and serialize all asynchronous events produced by non-transferable resources.

First, the virtual machine needs to support the elementary debug commands of any online debugger, which at least include halting and stepping through a program. Second, as we have demonstrated, state synchronization is equally fundamental for out-of-place debugging. The virtual machine should be able to support forward and backward state transfer for non-transferable resources. Third, given the data provided by the transfer functions, the virtual machine must be able to update its own state. Four, the virtual machine must be able to capture and serialize all asynchronous events produced by non-transferable resources. Thereby allowing them to be forwarded from server to client.

4.8.2 Example: the MQTT Subscribe Action

To illustrate how the new interface for defining stateful actions works, we will discuss the implementation of the MQTT *subscribe* action. The subscribe action is exposed in the runtime as a WebAssembly function that takes three unsigned 32-bit integers as arguments, corresponding to the location of the topic string in WebAssembly memory (offset and length), and the function index of the WebAssembly, which will act as callback function for events from the topic. Actions are implemented directly in the WARDuino virtual machine using C macros. In order to implement stateful actions, we have extended the existing macros with two new macros. We will discuss each macro in turn.

```

1 void subscribe_internal(Module *m,          12 def_action(subscribe, threeToNoneU32)
2     uint32_t topic_param,                  {
3     uint32_t topic_length,                13     uint32_t topic = arg2.uint32;
4     uint32_t fidx) {                   14     uint32_t length = arg1.uint32;
5     const char *topic =                 15     uint32_t fidx = arg0.uint32;
6     parse(m, topic_length,             16     subscribe_internal(
7         topic_param);                  17         m, topic, length, fidx);
8     mqttClient.subscribe(topic);        18     pop_args(3);
9     Callback c = Callback(m, topic,      19     return true;
10    fidx);                         20 }
11    CallbackHandler::add_callback(c);}
```

Listing 4-1. The implementation of the MQTT *subscribe* action in the WAR-Duino runtime, without stateful out-of-place support.

Listing 4-1 shows the standard implementation of the subscribe action using the *def_action* macro. We have split the definition into an internal function, shown on the left, and the interface definition on the right. The internal function implements the behavior of the subscribe action, it receives as parameters the WebAssembly *m* module in which it is executed, and the offset and length of the topic string, and the function index. On line 6, the *parse* function will extract the topic string from the WebAssembly memory and parse it as an UTF8 string. Using the MQTT client the action will subscribe the microcontroller to the given topic. For brevity, we have left out the exception handling, in case the MQTT client has not been initialized, or the communication with the MQTT broker fails. After subscribing successfully, any messages from the MQTT broker will be routed to the concurrent callback system in the runtime. On lines 10 to 11, the action registers the WebAssembly function with index *fidx* to the callback environment. This way, the callback system will concurrently call the function whenever a new message arrives.

The interface definition on the right side of Listing 4-1 defines the action as a proper WebAssembly function using the *def_action* macro. The macro takes the name of the action, and its type as arguments. In the example, the subscribe action takes three arguments and returns nothing. The body of the macro takes the arguments from the stack and passes them to the internal function which performs the action. At the end the macro lifts the consumed arguments from the stack, and returns true. The boolean value returned by actions is used to indicate failure, and are used by the runtime to throw WebAssembly traps in case something goes wrong.

```

1 // on server
2 def_to_client(subscribe) {
3     uint32_t topic = arg2.uint32;
4     uint32_t length = arg1.uint32;
5
6     // add transfer to be send with
7     // invoke
8     sync_memory(m, topic, length);
9 }
10 def_to_server(subscribe) {
11     // add transfer to update callback
12     env
13     sync_callback();
14 }
```

Listing 4-2. The implementation of the transfer functions for the MQTT `subscribe` action in the WARDuino runtime, to enable stateful out-of-place support.

4.8.3 Stateful Actions for Non-transferable Resources

In order to enable stateful out-of-place debugging with the `subscribe` action, we need to define both the transfer from server to client, and vice versa. Analogous to the action definition this can be done in WARDuino using C macros, however, we also provide a number of primitives for constructing transfers. The primitives hide the specifics of the debugger's communication protocol, and allow library implementers to focus exclusively on what state needs to be transferred for a given action. In essence, each primitive will extend a hidden transfer object with the necessary information, and when the debugger sends the `invoke` message, it will serialize the constructed transfer and include it in the message.

Listing 4-2 shows the implementation of both transfer functions for the `subscribe` action. The left side of the figure, shows how the server must transfer state to the client, and the right side how the client must perform the action and return the state changes to the server.

Consider first the server, the `def_to_client` macro defines the transfer function for the `subscribe` action, which in our semantics is used in the *step-client* rule. Since the transfer is created right before the action should be performed, it can easily look at its arguments on the stack. The `subscribe` action only relies on the topic string in WebAssembly, so the transfer only needs to sync this slice of memory. This can be done with one of the primitives we provide to help with the state synchronization, in this case `sync_memory`. The primitive takes as arguments, a WebAssembly module, offset, and length, and will add the slice of memory to the transfer.

For the client, the `def_to_server` macro works slightly differently, it is executed after the action has been performed, and needs to define which state needs to be synchronized. In the case of our example, only the callback map is updated by the `subscribe` action. For the transfer we can use the `sync_callback`

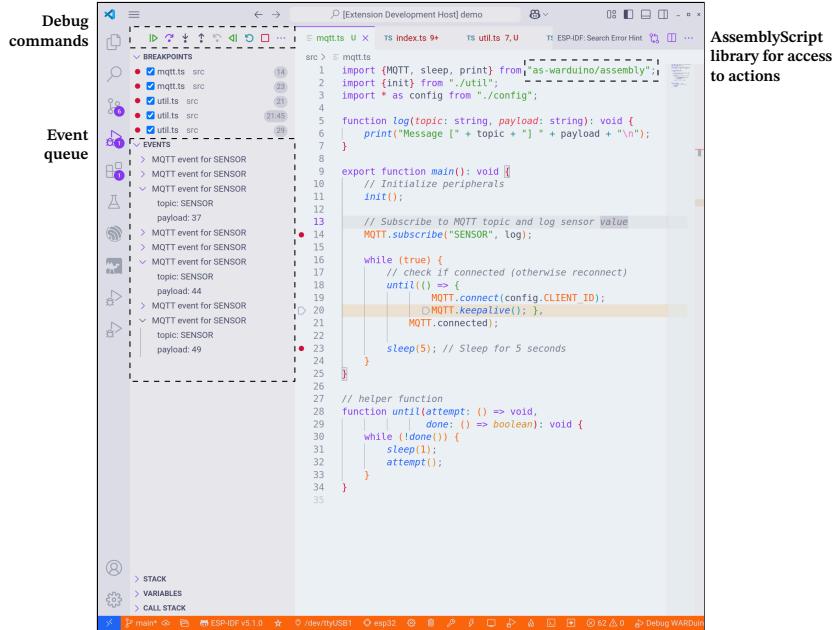


Figure 4-12. A screenshot of the out-of-place debugger in VS Code.

primitive which will add to the transfer, the minimal necessary data to update the callback environment on the server.

4.8.4 Prototype: Testing and Debugger Frontend

Our prototype implementation on top of the WARDuino runtime allows developers to use the existing VS Code extension for the warduino debugger to debug AssemblyScript programs using stateful out-of-place debugging. Figure 4-12 shows a screenshot of the debugger frontend in VS Code. The frontend supports the standard debug operations, pause, play, step forward, step into, step over, and breakpoints. Additionally, the extension features a view of the current events in the event queue on the server. These events can be triggered at any point by the developer, similar to performing a step.

We tested the prototype implementation, by checking the invoke non-interference as described in Section 4.4. To test this empirically, we randomly generated a thousand simple WebAssembly programs, which included a number of actions that changed the memory in the WebAssembly module. We ran the programs both with and with the out-of-place debugger, and verified that the memory at the end of the program was indeed identical for each program.

```

1 import * as wd from warduino;
2
3 const LED: u32 = 25;
4 const BUTTON: u32 = 26;
5
6 function buttonPressed(): void {
7     wd.digitalWrite(LED, !wd.digitalRead(LED));
8 }
9
10 export function main() : void {
11     wd.interruptOn(BUTTON, wd.FALLING,
12                     buttonPressed);
13     while(true);
14 }
```

Listing 4-3. A simple AssemblyScript program that toggles an LED when a button is pressed.

EVENTS

Interrupt on pin 26 (FALLING)
 Interrupt on pin 26 (FALLING)

Figure 4-13. The debugger frontend shows a list of identical interrupts after a single button press.

4.8.5 Debugging Common Bug Issues

As mentioned in the Chapter 1, a 2021 study on “*5,565 bugs in 91 Internet of Things projects*” showed that the most frequent types of bugs are related to software development and device issues (Makhshari and Mesbah, 2021). In this section, we show an example program illustrating how out-of-place debugging better accommodates finding and solving device issues than regular remote debugging. Appendix F.2 provides a similar comparison but for a software development issue due to concurrency.

The Bug. Many device issues are related to handling interrupts (Makhshari and Mesbah, 2021). Listing 4-3 shows a simple AssemblyScript application that toggles an LED when a button is pressed. The code listens for a hardware interrupt triggered on the falling edge of the button pin (line 11). Upon receiving an interrupt, the `buttonPressed` function is called, which toggles the LED (line 7). While the code may not contain errors, the hardware can cause bugs in it. Consider the following bug scenario: when testing the application with a real button, the LED sometimes does not change despite the button being pressed.

Bugfixing with a Remote Debugger. With a regular remote debugger, developers could start their diagnosis by adding a breakpoint in the `buttonPressed` callback function triggered when pressing the button. Note that in this simple example, there is only one single callback function, but in more complex Internet of Things applications developers may need to place

breakpoints in many callback functions as it is difficult to rule out which ones are not causing to the faulty behavior.

Stepping through code with asynchronous callbacks is generally not easy with current state of the art remote debuggers. Keeping track of all the asynchronous callbacks increases the number of times a developer needs to manually step through the application before discovering the error, complicating debugging. Moreover, stepping through the code is relatively slow, as the network latency between the developer's machine and the remote device slows down the debug session. Finally, most applications will not feature a busy loop as in our example, but the main thread runs concurrently with the asynchronous invocations, making it harder to notice errors.

Once the developer has stepped through all the asynchronous code letting the callbacks execute, the developer might notice that the `buttonPressed` callback is strangely invoked multiple times. The reason is that a single button press can trigger multiple hardware interrupts due to a common problem of physical buttons called *contact bouncing* (McBride, 1989). Contact bouncing happens when the voltage of a mechanical switch pulses rapidly, instead of performing a clean transition from high to low. In that case, the pin can register a falling edge multiple times in a row. Subsequently, the `buttonPressed` function is triggered multiple times for a single press. If contact bouncing causes the function to be triggered an even number of times, the state of the LED seems to remain the same, making the developer believe the code does nothing. It is not trivial to deduce the underlying contact bouncing problem by only stepping through the program.

Bugfixing with *Edward*. Let us now revisit the scenario using out-of-place debugging. *Edward* provides the developer with a dedicated view on the event queue with all asynchronous events that happen on the remote device, and the ability to choose when the next event happens. When the developer pushes the physical button once during debugging, they will immediately notice that *Edward*'s events view suddenly contains multiple identical events for a single button press, as shown in Figure 4-13. This information enables the developer to more easily detect the contact bouncing issue.

If the developer has not yet deduced the root cause of the bug, they could use stepping through the code in a similar way than when using the remote debugger. However, this time, stepping through the code is faster as debugging happens locally without incurring in network communication. Moreover, the frontend of *Edward* supports an early, naive implementation of backward debugging. This means that during debugging when the LED does not turn on, the developer can step back to the previous step to diagnose what exactly went wrong during the execution. There is no need to restart the program and try to guess what the right conditions for the bug were. However, external

changes are not reverted. When an LED turns on, stepping backwards does not turn it off again, since the backwards step is only implemented naively in the frontend using snapshots of the virtual machine state. In Chapter 5 we will discuss how to improve on this, by making actions reversible in a multiverse debugger.

Conclusion. This example illustrates that using out-of-place debugging makes a difference when debugging device issues compared to a remote debugger. Since *Edward* captures all non-transferable resources and provides a view on the event queue with all asynchronous events that happened at the remote device, developers can more easily diagnose device issues. For those cases where stepping is still needed, this happens with low latency. *Edward* also allows developers to step backwards, potentially reducing the debugging time as applications may not need to be restarted to reproduce the conditions for the bug to appear.

We now present some preliminary quantitative evaluation of *Edward*, to underscore the potential of our approach to reduce performance impact while debugging Internet of Things devices.

4.9 Discussion

Before giving a detailed overview of the related work, we now consider the wider context of our work and outline the advantages and disadvantages of our design decisions.

On the design choices

This chapter presents the first formal foundation for out-of-place debugging and address within it the important challenge of state desynchronization, which has been neglected by previous works. This resulted in the first stateful out-of-place debugger implementation. We choose to focus on the context of microcontroller programming, as it is a domain where out-of-place debugging can provide significant benefits, and where the support for stateful operations is crucial. The resource constraints imposed by microcontrollers are the main motivation for out-of-place debugging in this context, which inevitably impacted the design choices we made in a significant manner.

The impact of the resource constraints especially impacted the first of our key assumptions, that underlie our formalization. To minimize the impact of transferring state, we require that state dependencies of the actions can be known statically. This allows both client and server to quickly determine

which parts of the state need to be transferred, without the need for expensive analysis procedures.

Additionally, we have chosen to keep the modeling of the asynchronous events simple, by only considering the order of events and assuming that any interleaving of events in the program is possible. The main motivations for this choice, were to reduce the complexity of our formalization, and keep the focus on how out-of-place debugging can be extended with stateful operations, and how this can be formalized. Certainly more complex and accurate models for the events exist, which do take into account the interleavings, and the exact timing of events. Using existing models for event interleaving, it should be possible to weaken our assumptions, and thereby relax the requirements our system puts on stateful actions.

Opportunities for advanced environment modeling

The current abstract of asynchronous events in our debugger semantics is a very simple model of the environment. The model does not take into account the exact timing of events, and assumes all interleaving of events are possible. However, such timings and interleavings are crucial for many applications (Lamport, 1978). Luckily, this problem has been extensively studied in the field of distributed systems, and a wide range of models exist to capture the asynchronous behavior. Likewise, the literature on automated testing has a broad range of techniques for modeling the environment. We give a brief overview of the literature on synchronization and consistency in distributed systems, and environment modeling in testing.

4.10 Related Work

We have discussed the different implementations of out-of-place debugging extensively in Section 4.1 and Section 4.2. In this section, we will discuss other related works.

Remote debugging

In remote debugging (Rosenberg, 1996), a debugger frontend connects to a remote backend that executes the target program. However, remote debugging may worsen the probe effect (Gait, 1986) and can experience significant delays due to the overhead of running the debugger on the microcontroller coupled with continuous communication requirements. Regardless, due to the ability to debug remote processes, remote debuggers are ubiquitous in software development, with popular debuggers such as GDB (Free Software

Foundation, n.d.) and LLDB (“Remote Debugging - LLDB,” n.d.), as well as default support for remote debugging by many development environments (Mikejo5000, 2025). We have thoroughly discussed the related work on remote debugging in Section 3.11.

Remote debugging embedded systems

Section 3.11 we also discussed remote debuggers in the context of embedded devices. The notable examples included, the popular OpenOCD debugger (Högl and Rath, 2006), Espruino for JavaScript (Williams, 2014), and MicroPython for Python (George, 2021). The debugging support varies widely between these solutions, but . In comparison, our work not only delivers a remote debugging experience but also provides online debugging with minimal latency on demand. Moreover, to the best of our knowledge, no other approach offers developers the ability to access and control the processing of events generated by the remote device.

Synchronization and consistency in distributed systems

In our work, the out-of-place debugger comprises two remote processes, the server and the client. The semantics of the debugger clearly describe the synchronization between these two devices, however, if we were to extend the debugger to multiple devices, the synchronization would become much more complex. Synchronization in distributed systems has of course been widely studied. Clock synchronization goes back to the earliest distributed systems in the seventies and eighties (Kopetz and Ochsenreiter, 1987, Lamport, 1978, Schmuck and Cristian, 1990), and has been a crucial part of distributed systems ever since (Auguston et al., 2005). In fact, with the rise of internet of things applications, the problem has received renewed attention (Mani et al., 2018, Yigitler et al., 2020).

More generally, the problem of replicating data and consistency within a distributed network is an enormous field of research on its own. Much effort has been put into developing solutions for (strong) eventual consistency, where the requirement for synchronization is weakened to allow for higher availability. A common approach is to use conflict-free replicated data types (CRDTs) (Shapiro et al., 2011), which allow for concurrent updates to data without the need for any coordination (Almeida, 2024). It is an open question whether eventual consistency is enough for out-of-place debugging, or whether stronger consistency guarantees are needed. However, many other forms of consistency exist, such as sequential consistency (Lamport, 1979), causal consistency (Perrin et al., 2016, Terry et al., 1994), and linearizability (Herlihy and Wing, 1990). It is our belief that the type of consistency used in

out-of-place debugging is tied strongly to its application context. Yet given the vast amount of work in this field, we believe that the existing techniques for consistency can be used to generalize our formalization to multiple devices, and to further strengthen the formal guarantees.

Program slicing

Given the microcontroller setting, our approach determines the state needed to be transferred statically as part of the definition of the actions on non-transferable resources. However, for more complex actions, it would be advisable to use static analysis to determine the slice of the state. This is very similar to program slicing (Weiser, 1981, Xu et al., 2005) which decomposes a program into segments based on a *slicing criterion*. This criterion can slice in two directions, either *backward* when identifying segments that might affect the criterion, or *forward* when the segments are affected by the criterion. In our semantic, the transfer at the start of an invocation is similar to backward slicing, and the difference returned at the end is similar to forward slicing. Many different techniques for slicing exist (Xu et al., 2005), both dynamic and static, or hybrid. Only a few works have looked into static (Stiévenart et al., 2022) and dynamic (Stiévenart et al., 2023) slicing of WebAssembly programs, however, many of the existing techniques can be expected to work with WebAssembly as well, without great difficulty.

Environment modeling

Environment modeling is a technique used in testing to model the behavior of the environment in which a program runs (Blackburn, 1998). Such models are often used for automatic test generation (Auguston et al., 2005, Dalal et al., 1999) for a certain specification, and has also been applied to real-time embedded software (Iqbal et al., 2015). Our work models the asynchronicity of the environment through a simple partial order of instantaneous events. This model enables exploring different behavior based on the order of events, and to a certain extent the timings of asynchronous events. More advanced models of the environment could help take into account additional dependencies between events, and real-time effects.

4.11 Conclusion

While existing out-of-place debuggers can already support a wide range of programs and application domains with purely stateless operations on non-transferable resource, they lack support for stateful operations or provide only some very minimal ad hoc support. In this work, we address this limi-

tation by presenting the first formal semantic for out-of-place debugging, in which we incorporate our novel stateful out-of-place debugging technique. Our approach allows for the debugging of programs with stateful operations on non-transferable resources, with a lazy synchronization strategy where state is only send to the client device when it is required. Our formalization allows us to also define correctness for stateful out-of-place debugging, which we divide into soundness and completeness. The proof for these theorems show that stateful out-of-place debugging is able to debug programs without introducing impossible execution paths, or missing concrete paths. We have implemented our approach in a prototype debugger, called *Edward*, which is built on top of the WARDUINO runtime, and VS Code extension. Initial empirical testing shows that our implementation indeed satisfies the correctness criteria defined in our formalization.

Chapter 5

Multiverse debugging on microcontrollers

Our knowledge can only be finite, while our ignorance must necessarily be infinite.

— Karl Popper, *Knowledge without Authority*

  *Artifact Available, and Reusable.*

The second, and final, new debugging technique we investigated for microcontrollers, is multiverse debugging. As part of our investigation, we extended multiverse debugging to handle input/output (I/O) operations, and created a prototype debugger that enables reversible actions on microcontrollers.

5.1 Introduction

Debugging non-deterministic programs is a challenging task, since bugs may only appear in very specific execution paths (Gurdeep Singh, 2022, McDowell and Helmbold, 1989). This is especially true for microcontroller programs, which typically interact heavily with the environment. This makes reproducing bugs unreliable and time-consuming, a problem that traditional debuggers do not account for. By contrast, multiverse debugging (Torres Lopez et al., 2019) is a novel technique that solves this problem by allowing programmers to explore all possible execution paths. A multiverse debugger allows users to move from one execution path to another, even jumping to arbitrary program states in parallel execution paths. This entails traveling both forwards and backwards in time, i.e. a multiverse debugger is also a time travel debugger. So far, existing implementations work on abstract execution models to explore all execution paths of a program (Pasquier et al., 2023a, 2023b, 2022; Torres Lopez et al., 2019). Within these semantics, only the internal state of the program is controlled.

Unfortunately, debugging programs that involve I/O operations using existing multiverse debuggers can reveal inaccessible program states that are not encountered during regular execution. This is known as the probe effect

(Gait, 1986), and can occur in multiverse debuggers when they do not account for the effect of I/O operations on the external environment when changing the program state. Encountering such states during the debugging session can significantly hinder the debugging process, as the programmer may mistakenly assume a bug is present in the code, when in fact, the issue is caused by the debugger. In this chapter, we investigate how we can scale multiverse debugging to programs running on a microcontroller which interacts with the environment through I/O operations. This introduces three new challenges.

First, the effect of output operations on the environment can influence later states in the execution path, for example when a robot drives forward. Therefore, when stepping backwards, the changes made to the environment by the program must be reverted to stay consistent with normal execution. Otherwise, the debugger may enter inaccessible execution paths. This far-reaching probe effect, is especially difficult to control when making arbitrary jumps in the execution tree.

Second, input operations from the external environment make it difficult to maintain reproducibility (Frattini et al., 2016). There are often too many possible execution paths to explore due to an infinite range of inputs. Furthermore, it is impractical for developers to enumerate all possible inputs, or to perfectly configure the environment to achieve a specific execution path every time. Without a way to handle the large ranges of possible inputs, the reproducibility of non-deterministic bugs in the multiverse debugger becomes challenging.

Third, due to the hardware limitations of the microcontrollers that we target it is unfeasible to run the multiverse debugger entirely on the microcontroller. We thus need to expand multiverse debugging so that it can be used even in such a restricted environment.

5.2 MIO: Multiverse Input/Output Debugger in Practice

Before we discuss the details of our contributions and the implementation, we give an overview of how our multiverse debugger, MIO, works in practice. We will use a simple example to illustrate the different concepts of our multiverse debugger.

5.2.1 Example: A Light Sensor Program

Consider a simple program that reads a value from a color sensor, to measure the light intensity, and turns on an LED with a color corresponding to the

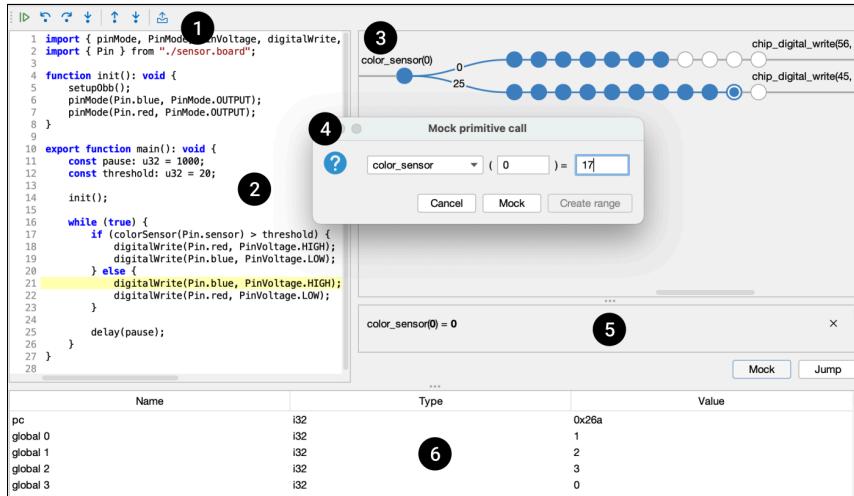


Figure 5-1. Screenshot of the MIO debugger debugging a small light sensor program. Top (1): the debug operations; pause or continue, step back, step over, step into, step to the previous line, step to the next line, and update software. Left pane (2): source code. Top-right pane (3): the multiverse tree. Popup window (4): window to add mocked input. Bottom-right pane (5): the current mocked input. Bottom pane (6): general debugging information, such as the global and local variables, and the current program counter.

value read. The left side of Figure 5-1 (2) shows the example program written in AssemblyScript (Battagline, 2021). Reading the value from the color sensor happens through the `colorSensor` function, and changing the color of the LED happens through the `digitalWrite` function. In an infinite loop, the program reads a value from the color sensor. If the value is below a threshold, the red LED is turned on, and otherwise the blue LED is turned on. At the end of the loop the program waits for 1000 milliseconds before starting the next iteration.

5.2.2 The Frontend of the Multiverse Debugger

Figure 5-1 shows the MIO multiverse debugger in action. While debugging, the program and the debugger backend run on a microcontroller connected to a computer running the debugger frontend, shown in the screenshot. The left pane (2) shows the program being debugged, in this case the light sensor program. In the top left corner (1), the user can see the debug operations available, which are in order: pause or continue, step back, step over, step into, step to the previous line, step to the next line, and finally, update the code on the microcontroller. The top-right pane (3) shows the multiverse tree,

where each edge represents a WebAssembly instruction. In MIO all nodes are considered unique states, which means that loops are unrolled and no states will ever collapse into each other, making this graph always a rooted tree. MIO allows input values to be mocked using the *Mock* button, which triggers a popup window (4) where users can specify the mocked return value for a given input primitive. The *Create range* button can be used to add a range of new branches to the multiverse tree. The mocked primitives show up in the bottom-right pane (5), where they can also be removed again. The bottom pane (6) shows the global and local WebAssembly variables, and other program state information.

While debugging the light sensor program, the user can pause the program at any moment. At this point, the right pane will show the already explored paths of the multiverse tree. It is important to note that the multiverse tree does not correspond to a control flow graph, but shows every succeeding program state. Every edge in the tree represents the concrete execution of a single WebAssembly instruction, and every node represents the program state after that instruction. The multiverse tree in Figure 5-1 labels every node before the execution of a primitive with the primitive name, and labels the outgoing edges with the associated return value.

5.2.3 Debugging with the Multiverse Debugger

A developer can use the multiverse debugger to explore the execution of the light sensor program, using the debug operations in the top left corner, following normal debugging conventions. The right panel continually updates to show where in the program's execution the user is. However, the multiverse debugger allows for more than just stepping forwards and backwards through the program. The user can also jump to any node in the multiverse tree by simply clicking on that node, and explore the program from that point onwards with the available debugging instructions.

5.2.4 Exploring the multiverse tree

The screenshot in Figure 5-1 shows the program paused at line 64, after reading a value from the color sensor. This value was 25, and if the user steps forward, the program will turn on the red LED (pin 45) as shown by the multiverse tree. In an earlier stage, the user actually read a value of 14. Using the debugger, it is possible to explore that execution path again, without having to recreate the situation where the sensor reads 14. This is done by clicking on any node on the execution path where the sensor reads 14, which is shown as a blue node with a white circle in it. If the user presses the *Jump* button, the debugger will traverse the blue-indicated path in the

multiverse tree, from the current node to the selected node. When reading the sensor value, the debugger will use mock input actions, to override the normal behavior of the sensor and return the value 14.

The mocking mechanism is a crucial part of the multiverse debugger, since it allows the user to explore different execution paths without having to recreate the exact conditions that led to that path. It is therefore not only a part of the automatic traversal of the multiverse tree, but also a part of the manual exploration of the tree. While a user is stepping forwards through a program, and a non-deterministic input primitive is encountered, they can press the *Mock* button below the right pane instead of the *step* button. When doing so, window (4) shown in Figure 5-1 is used. This window allows the user to specify that the virtual machine should return a specific value when a primitive is called with certain arguments. This allows users to easily reproduce bugs that might not occur with the sensor values read from the current environment.

Now that we have established how our multiverse debugger works in practice, and its terminology, we will discuss the challenges in creating a multiverse debugger for microcontrollers.

5.2.5 Challenge C1: Inconsistent External State during Backwards Exploration

When moving backwards in time, the external state must also be restored. A multiverse debugger that allows for backwards exploration, but does not handle the external state, will be able to create impossible situations. For instance, if the light sensor program is paused when the red LED has just been turned on, the debugger can move backwards in time to when the light intensity is measured. Reading a different value as you step forwards again, this time, the blue LED could be turned on, even though the red LED is still on. This is an impossible situation, since the LEDs can never be on at the same time in a normal execution of the program. Stepping back over line 64, therefore, requires a compensating action, which turns off the red LED. Luckily, such actions can be defined for many different output operations (Laursen et al., 2018, Schultz, 2020).

5.2.6 Challenge C2: Exploring Non-deterministic Input in Multiverse Debuggers

When a program's execution path is determined by input from the environment, the multiverse debugger needs to explore different execution paths by traveling back in time and changing the input to the program. However, it is impractical for developers to cover all possible inputs, or to configure the

environment exactly right for a specific execution path every time. To solve this problem, we propose a new approach to multiverse debugging that uses time travel debugging in combination with virtual machine instrumentation to mock input values. It is important that no impossible values are used for mocking, since they can lead to inaccessible program states.

5.2.7 Challenge C3: Keeping Track of the Program State Efficiently

In order for multiverse debugging to work on a microcontroller it has to keep track of the program state and its output effects on the external environment. However, tracking this information on microcontrollers is not feasible due to the limited memory capacity of these devices. Therefore, the MIO debugger is a remote debugger, which enables minimal interference with the microcontroller, and allows information to be stored on a more powerful computer. Even so, it is not feasible to take snapshots for every executed instruction as it would slow down the program significantly, and the size of the snapshot history would quickly become unmanageable.

In time travel debugging, this problem is usually solved by taking snapshots at regular intervals, called checkpoints. When moving backwards in time, the debugger can then jump to the nearest checkpoint, and replay the program's execution from that point.

To make a checkpointing system work correctly for multiverse debugging, we had to adopt a slightly different approach. Instead of only taking snapshots at regular intervals, we also take snapshots after each input or output action. By carefully choosing when snapshots are taken we can ensure the correctness of the replay mechanism. Using this approach, we can significantly reduce the run-time overhead, making multiverse debugging practically usable on microcontrollers.

5.3 A Multiverse Debugger for WebAssembly

In this section, we discuss the operation of our multiverse debugger through a small-step semantic defined over a stack-based language. We use WebAssembly as an example language, since it has a full and rigorous language semantics (Haas et al., 2017; Rossberg, 2023, 2019). However, our small-step rules include very few details specific to WebAssembly. Therefore, we believe that the principles of our multiverse debugger can be applied to any stack-based language, with minimal effort.

5.3.1 Requirements for I/O operations

While our multiverse debugger can deal with a large set of I/O operations, there are some limitations that make it impossible to support certain I/O operations. Intuitively, our multiverse debugger supports non-deterministic input primitives as long as the range of possible input values is known. Output primitives are supported as long as they are atomic, and are deterministically reversible, i.e. after reversing an output operation the environment will be in the same state as before applying the operation.

Input primitives Input primitives are allowed to be non-deterministic as long as the *range* of the input primitives is known, i.e. a temperature sensor might have a range between –20 degrees till 160 degrees. Knowing the range of our input primitives is important so that the debugger can be instrumented to only sample values that can actually be observed during normal execution.

Output primitives First, we require output primitives to be synchronously and atomically, i.e. all side effects from the operation have to be fully completed during the call of the operation in the virtual machine. Second, for a given execution of the I/O operation, there must be a *deterministic compensating action*. This compensating action undoes the effects of the forward execution, bringing the environment back to a state before executing the actions.

Predictable dependencies We assume *predictable* dependencies of the I/O operations are known, for example consider a setup where an LED is directly pointed towards a light sensor. During regular execution, turning the LED on will directly influence the possible values which can be read, i.e. there is a dependency between the output pin and the possible sensor values which can be read. Our MIO debugger, has initial support for expressing such simple dependencies, in the semantics however, we take abstraction and assume that sensor values are independent.

5.3.2 WebAssembly Language Semantics

We discussed the basics of the WebAssembly language semantics in Chapter 4 (Section 4.4.1). In this chapter, we again use the same semantics, taken from Haas et al. (2017).

5.3.3 Extending WebAssembly with Primitive I/O Operations

Since multiverse debuggers explore all possible execution paths, they have to be able to reproduce the program’s execution, even when non-determinism is involved. It is therefore important to consider where non-determinism is introduced in the program, and how it can be handled. Since the WebAssem-

(WebAssembly Program state)	$K ::= \{s, v^*, e^*\}$
(Global store)	$s ::= \{\text{inst inst}^*, \text{tab tabinst}^*, \text{mem meminst}^*, \text{prim P}\}$
(Primitive table)	$P ::= p^*$
(Primitive)	$p = f : v^* \rightarrow \{\text{ret } v, \text{cps } r\}$
(Compensating action)	$r = f : \epsilon \rightarrow \epsilon$

Figure 5-2. The configuration for the reversible primitives embedded in the WebAssembly semantics from the original paper by Haas et al. (2017), the differences are highlighted in gray. *Top:* The WebAssembly semantics extended with a primitive table. *Bottom:* The signatures of primitive and their compensating actions.

bly semantics on their own are fully deterministic, we can choose precisely where non-determinism is introduced in our system. In the context of microcontrollers, non-deterministic input is unavoidable. Our system therefore limits non-determinism exclusively to the input. This means that each branch in the execution tree can therefore be traced to a different input value. The output primitives in MIO, on the other hand, are deterministic in terms of the program state. Section 5.3.7 discuss how the debugger can reproduce non-deterministic input reliably through input mocking.

We do not consider parallelism as a source of non-determinism, since this has been examined thoroughly by the original paper on multiverse debugging by Torres Lopez et al. (2019).

5.3.3.1 Primitive I/O operations

We extend WebAssembly with a set of primitives P that fulfil the prerequisites outlined above. Figure 5-2 shows the definition of the primitives in WebAssembly. Each primitive in P can be identified by a unique index j , similar to the function indices in WebAssembly, and looking up primitives is done through the global $P(j)$. When calling a primitive, it returns both the return value v and the compensating action r . The function r compensates, or reverses, the effects of the primitive, but takes no arguments and returns nothing as indicated by its type $\epsilon \rightarrow \epsilon$. There is no need for any arguments, since the compensating action is generated uniquely for each execution of the primitive.

5.3.3.2 Forwards Execution of Primitives

Given the definition of the primitives in P , we can define the forwards execution of the primitives in WebAssembly, as shown in Figure 5-3. Non-determinism is introduced exclusively through the *input-prim* rule, which is used to evaluate input primitives. The evaluation of the primitive p non-

Non-Deterministic Input Primitives

$$\frac{P(j) = p \quad p \in P^{\text{In}} \quad v \in |p(v_0^*)_{\text{ret}}|}{\{s; v^*, v_0^*(\text{call } j)\} \hookrightarrow_i \{s; v^*, v\}} \text{ input-prim}$$

$$\frac{P(j) = p \quad p \in P^{\text{Out}} \quad |p(v_0^*)_{\text{ret}}| = v}{\{s; v^*, v_0^*(\text{call } j)\} \hookrightarrow_i \{s; v^*, v\}} \text{ output-prim}$$

Figure 5-3. Extension of the WebAssembly language with non-deterministic input primitives.

(Debugger state)	$dbg ::= (es, msg, mocks, K_n \mid S^*)$
(Execution state)	$es ::= play \mid pause$
(Incoming messages)	$msg ::= \emptyset \mid step \mid stepback \mid pause \mid play \mid mock(j, v^*, v) \mid unmock(j, v^*)$
(Program state)	$K ::= \{s, v^*, e^*\}$
(Overrides)	$mocks ::= \emptyset \mid mocks, (j, v^*) \mapsto v$
(A snapshot)	$S_n ::= \{K_m, p_{\{cps\}}\}$
(Snapshots list)	$S^* ::= S_0 \cdot \dots \cdot S_{\{n-1\}} \cdot S_n$
(Starting state)	$dbg_{\text{start}} ::= (pause, \emptyset, \emptyset, K_0 \mid \{K_0, E\})$
(Empty action)	$r_{\text{nop}} ::= \lambda(). \text{nop}$

Figure 5-4. The multiverse debugger state for WebAssembly with input and output primitives.

deterministically returns a value v from the codomain of the primitive function, $|p(v_0^*)_{\text{ret}}|$. Here, the rule simply discards the compensating action, and places the return value of the primitive on the stack. The *output-prim* rule works analogously, except the evaluation produces its return value deterministically. Note that compensating actions $p(v_0^*)_{\text{cps}}$ are not used for the regular forward execution, but are crucial when moving backwards in time. In the next sections, we show how the compensating actions are used during multiverse debugging.

5.3.4 Configuration of the Multiverse Debugger

Using the recipe for defining debugger semantics from Torres Lopez et al. (2019), we can define our multiverse debugger on top of the extended WebAssembly semantics presented in Section 5.3.3. Figure 5-4 shows the configuration of the multiverse debugger for WebAssembly with input and output primitives. The program state in the underlying language semantics is labeled with an iteration index n , which corresponds to the number of steps in the underlying semantic since the start of the execution, or the depth in the

Forwards evaluation rules

$$\begin{array}{c}
 \dfrac{\text{non-prim } K_n \quad K_n \hookrightarrow_i K_n + 1}{(\text{play}, \emptyset, \text{mocks}, K_n \mid S^*) \hookrightarrow_{d,i} (\text{play}, \emptyset, \text{mocks}, K_n + 1 \mid S^*)} \textit{run} \\
 \\
 \dfrac{\text{non-prim } K_n \quad K_n \hookrightarrow_i K_n + 1}{(\text{pause}, \text{step}, \text{mocks}, K_n \mid S^*) \hookrightarrow_{d,i} (\text{pause}, \emptyset, \text{mocks}, K_n + 1 \mid S^*)} \textit{step-forwards} \\
 \\
 \dfrac{}{(\text{play}, \text{pause}, \text{mocks}, K_n \mid S^*) \hookrightarrow_{d,i} (\text{pause}, \emptyset, \text{mocks}, K_n \mid S^*)} \textit{pause} \\
 \\
 \dfrac{}{(\text{pause}, \text{play}, \text{mocks}, K_n \mid S^*) \hookrightarrow_{d,i} (\text{play}, \emptyset, \text{mocks}, K_n \mid S^*)} \textit{play}
 \end{array}$$

Figure 5-5. The small-step rules describing forwards exploration in the multiverse debugger for WebAssembly instructions without primitives.

multiverse tree. The debugger state dbg contains the execution state of the program, incoming debug message msg , mocked input mocks , the program state K_n , and the snapshot list S^* . The snapshots S^* are a cons list of snapshots S_n , containing the program state K_n and the compensating action p_{cps} . The rules of the debugger semantics, presented in the following sections, will show how the snapshot list is extended—and how the snapshots are used to travel back in time.

Mocked inputs are stored as a key value pairs, where the index identifying the input primitive j , and the list of argument values v^* are mapped to the overriding return value v . The key value map is represented here as a partial function, which compares lists of values v^* element-wise. For any key that is not defined in the map, we write $\text{mocks}(j, v^*) = \epsilon$.

The starting state of the debugger $\text{dbg}_{\text{start}}$ is defined as the paused state with no incoming or outgoing messages, an empty mocks environment, the initial program state K_0 , and a snapshot list containing only the initial snapshot $S_0 = \{K_0, r_{\text{nop}}\}$. Here r_{nop} is the empty action, which takes no arguments and returns nothing. This function indicates that no compensating action is needed.

5.3.5 Forwards Exploration in Multiverse Debuggers

Figure 5-5 shows the basic small-step rules for stepping forwards in the multiverse debugger, without input and output primitives. These rules allow the debugger to explore traditional WebAssembly programs, without any non-deterministic input or output. For clarity, we use several shorthand notations

Forwards I/O evaluation rules

$$\begin{array}{c}
\begin{array}{c}
K_n = \{s; v^*, v_0^*(\text{call } j)\} \quad P(j) = p \quad p \in P^{In} \quad \text{mocks}(j, v_0^*) = \varepsilon \\
K_n \hookrightarrow_i K_{n+1}
\end{array}
\frac{}{(play, \emptyset, \text{mocks}, K_n \mid S^*) \hookrightarrow_{d,i} (\text{play}, \emptyset, \text{mocks}, K_{n+1} \mid S^* \cdot \{K_{n+1}, r_{nop}\})} \text{run-prim-in}
\end{array}$$

$$\begin{array}{c}
\begin{array}{c}
K_n = \{s; v^*, v_0^*(\text{call } j)\} \quad P(j) = p \quad p \in P^{Out} \quad p(v_0^*) = \{\text{ret } v, \text{cps } r\} \\
K_{n+1} = \{s; v^*, v\}
\end{array}
\frac{}{(play, \emptyset, \text{mocks}, K_n \mid S^*) \hookrightarrow_{d,i} (\text{play}, \emptyset, \text{mocks}, K_{n+1} \mid S^* \cdot \{K_{n+1}, r\})} \text{run-prim-out}
\end{array}$$

Figure 5-6. The small-step rules describing forwards exploration for input and output primitives in the multiverse debugger for WebAssembly, without input mocking.

in the rules. We use the notation $(K_n \hookrightarrow_i K_{n+1})$ to say that the program state K takes a step to the program state K' in the underlying language semantics, where $K' = K_n + 1$. The notation (non-prim K) is used to indicate that the program state K is not a primitive call, or more fully, it is not the case that $K = \{s; v^*; v_0^*(\text{call}; j)\} \wedge P(j) = p$. We describe the rules in detail below.

run The rule for running the program forwards in the underlying language semantics. The debugger takes a step in the underlying language semantics ($K_n \hookrightarrow_i K_{n+1}$) as long as the execution state is *play*, there are no incoming or outgoing messages, and the program state is not a primitive call. While running in this way, the snapshot list S^* remains unchanged.

step-forwards When the debugger receives the *step* message, it takes one more step ($K_n \hookrightarrow_i K_{n+1}$), and transitions to the *pause* state if it was not already paused.

pause When the debugger receives a *pause* message in the *play* state, it transitions to the *pause* state. Note that afterwards, all the run rules are no longer applicable.

play The rule for continuing the execution. When the debugger receives the *play* message in the *pause* state, the execution state transitions to the *play* state.

The rules in Figure 5-6 are the minimal set of rules for stepping forwards when the next instruction in the program state K_n is a primitive call. The rules also describe the snapshotting behavior of the multiverse debugger, which is needed to travel back in time. We describe the run rules in detail below. The step rules are identical to the run rules, but they transition to the paused state

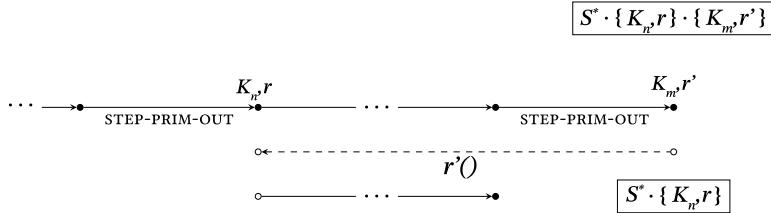


Figure 5-7. Schematic of how the *step-back-compensate* rule works. Starting from state K_m , the dotted arrow shows how the debugger jumps to the previous state K_n , and compensates the output primitive with $r'()$, while the full arrows show the normal execution. Top right: the snapshots before. Top left: the snapshots after.

after taking a step, and are triggered by the *step* message. These rules can be found in Appendix G.

The rules described here form the backbone of the multiverse debugger, and already allow for a multiverse debugger that can explore the execution of a program forwards in time. It is important to note that the debugger always takes snapshots when a primitive call is made. Only when this primitive is an output primitive, can the state of the environment change. On the other hand, only input primitives can introduce new branches to the multiverse tree. In the next section, we discuss how the multiverse debugger can explore the execution of a program backwards in time.

5.3.6 Backwards Exploration with Checkpointing

The multiverse debugger is also a time travel debugger, which means it can move backwards in time. It does this by restoring the program state from a previous snapshot, and then replaying the program's execution from that point. Figure 5-7 shows schematically the way the debugger steps back in time using the snapshots. In the situation depicted by the figure, the debugger has just stepped over an output primitive and added a snapshot to the snapshot list. Since the debugger will now step back over the execution of this output primitive, its effects must be reversed with the compensating action r'' in the last snapshot. This is shown with the dashed arrow. As part of this jump back in time, the snapshot containing the compensating action r'' is removed from the snapshot list and the program state K_n from the next snapshot is restored.

Since snapshots are only added when the program performs a primitive call, the second to last snapshot in the list was taken after the previous primitive call resulting in state K_n . This means, that after restoring the internal virtual machine state, the program is now at the point right after the previous

Backwards evaluation rules

(STEP-BACK)

$$\frac{K_n \hookleftarrow_i^{m-n-1} K_{m-1} \quad m > n}{(\text{pause, step back, mocks, } K_m \mid S^* \cdot \{K_n, r\}) \hookleftarrow_{d,i} (\text{pause, } \emptyset, \text{ mocks, } K_{m-1} \mid S^* \cdot \{K_n, r\})}$$

(STEP-BACK-COMPENSATE)

$$\frac{\text{first } r'() \text{ then } K_n \hookleftarrow_i^{m-n-1} K_{m-1}}{(\text{pause, step back, mocks, } K_m \mid S^* \cdot \{K_n, r\} \cdot \{K_m, r'\}) \hookleftarrow_{d,i} (\text{pause, } \emptyset, \text{ mocks, } K_{m-1} \mid S^* \cdot \{K_n, r\})}$$

Figure 5-8. The small-step reduction rule for stepping backwards in the multiverse debugger.

primitive call. Starting from this point, the debugger can replay the program’s execution forwards to K_{m-1} , which will not include any primitive calls. This means the steps will be deterministic, and will not change the external environment. This corresponds with the full arrow at the bottom of the figure. Next to it, is shown the snapshot list after the step back, which now only contains the snapshot of the state K_n .

In the outlined scenario the last transition in the chain, from K_{m-1} to K_m , performs an output action. However, if this transition is a standard WebAssembly instruction instead, no compensating action will be performed. Instead, the debugger will immediately restore the virtual machine state to K_n and replay the program’s execution forwards to K_{m-1} . In this case, none of the snapshots will be removed. This enables the debugger to continue stepping back in time.

Each of the two outlined scenarios corresponds with a rule in the multiverse debugger semantics, shown in Figure 5-8. The first scenario where the effects of an output primitive is reversed, is described by the *step-back-compensate* rule. The second scenario where the last transition is a standard WebAssembly instruction, is described by the *step-back* rule. We describe the rules in detail below.

step-back The rule for stepping back in time. When the debugger receives a *step back* message, the debugger restores the external state from the last snapshot in the snapshot list, which is not the current state. The debugger then replays the program’s execution from that point to exactly one step ($K_n \hookleftarrow_i^{m-n-1} K_{m-1}$) before the starting state. Since the restored snapshot remains in the past, it is kept in the snapshot list, to allow for further backwards exploration.

Mocking Semantics

(REGISTER-MOCK)

$$\frac{\text{msg} = \text{mock}(j, v^*, v) \quad P(j) = p \quad p \in P^{\text{In}} \quad v \in |p| \\ \text{mocks}' = \text{mocks}, (j, v^*) \mapsto v}{(\text{es}, \text{msg}, \text{mocks}, K_n \mid S^*) \hookrightarrow_{d,i} (\text{es}, \emptyset, \text{mocks}', K_n \mid S^*)}$$

(UNREGISTER-MOCK)

$$\frac{\text{msg} = \text{unmock}(j, v^*) \quad \text{mocks}' = \text{mocks}, (j, v^*) \mapsto v}{(\text{es}, \text{msg}, \text{mocks}, K_n \mid S^*) \hookrightarrow_{d,i} (\text{es}, \emptyset, \text{mocks}', K_n \mid S^*)}$$

(STEP-MOCK)

$$\frac{K_n = \{s; v^*; v_0^*(\text{call } j)\} \quad P(j) = p \quad p \in P^{\text{In}} \quad \text{mocks}(j, v_0^*) = v \\ K'_{n+1} = \{s'; v'^*; v\}}{(\text{pause}, \text{step}, \text{mocks}, K_n \mid S^*) \hookrightarrow_{d,i} (\text{pause}, \emptyset, \text{mocks}, K'_{n+1} \mid S^* \cdot \{K'_{n+1}, r_{\text{nop}}\})}$$

Figure 5-9. The small-step rule for mocking input in the MIO debugger, only including the step rule. The analogous rule for when the debugger is not paused (*run-mock*) is shown in Appendix G.

step-back-compensate The rule for stepping back in time when the last transition was a primitive call. This is always the case when the current state is K_m is part of the last snapshot. When the debugger receives a *step back* message, the debugger performs the compensating action r' from the last snapshot in the snapshot list, which reversed the effects of the last primitive call. Then, the debugger restores the external state K_n from the second to last snapshot in the snapshot list. The debugger then replays the program's execution from that point to exactly one step before the starting state. The last snapshot is removed from the snapshot list, since it now lies in the future.

In the case where no primitive call has yet been made, the snapshot list contains exactly $\{K_0, r_{\text{nop}}\}$, as defined by $\text{dbg}_{\text{start}}$, which the *step-back* rule can jump to. If the current state is K_0 , stepping back is not possible. Specifically, the *step-back* rule is not applicable, since m and n are both zero, and the *step-back-compensate* rule requires the snapshot list to contain at least two snapshots.

5.3.7 Instrumenting Non-deterministic Input in Multiverse Debuggers

In order to replay execution paths in the multiverse tree accurately, the multiverse debugger needs to be able to override the input to the program.

Mocking of input happens through the key value map mocks shown in Figure 5-4. New values can be added to the map using the *register-mock* rule, and existing values can be removed using the *unregister-mock* rule. Whenever the debugger encounters an input primitive call, it will always check the mocks map for an overriding value. If a value is found, the debugger will replace the call to the primitive with the mock value v . This is done by the *step-mock* rule.

register-mock The rule for registering a new mock value in the multiverse debugger. When the debugger receives a message $\text{mock}(j, v^*, v)$, the debugger will update the entry for (j, v^*) in the mocks environment to v . If an entry already exists in the environment, the rule will override the existing value.

unregister-mock The rule for unregistering a mock value in the multiverse debugger. When the debugger receives a message $\text{unmock}(j, v^*)$, the debugger will remove the mock value from the mocks map. If no value is found in the environment, the rule will have no effect.

step-mock The *step-mock* rule for stepping forwards in the multiverse debugger when an input primitive call is encountered. If the input primitive call is found in the mocks map, the debugger will replace the call with the mock value v .

The program state is then updated to the new program state K_{n+1} , and a new snapshot is added to the snapshot list. The snapshot includes the new program state and the empty compensating action r_{nop} , since no compensating action is needed for input primitives.

5.3.8 Arbitrary Exploration of the multiverse tree

With the semantics of input mocking in place, we now have the entire multiverse debugger semantics for WebAssembly with input and output primitives. In this section, we discuss how the multiverse debugger can be used to explore different universes. This can be done by Algorithm 5-1. When the debugger jumps from a state K_m to a state K_n , the debugger will find the smallest common ancestor of K_m and K_n , or the join. The debugger will then step backwards from K_m to the join. We use the notation \hookleftarrow_r to indicate that the debugger is reversing the execution, it is equivalent to a debugging step $\hookleftarrow_{d,i}$ that only uses the *step-back* and *step-back-compensate* rules. In the final step of the algorithm, execution is replayed from the join to K_n using the *step-mock* rule whenever it encounters a non-deterministic primitive call.

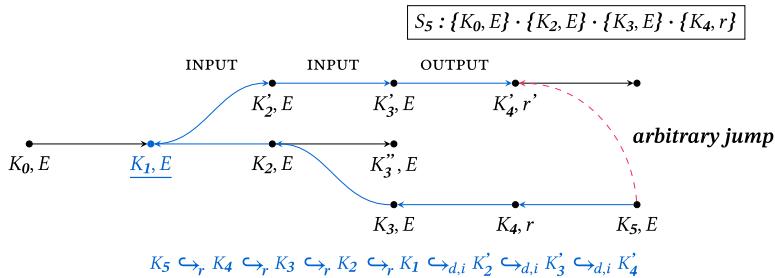


Figure 5-10. Schematic of how the multiverse debugger can jump to any arbitrary state in the past, using the *step-back* and *step-mock* rules. For the arbitrary jump from state K_5 to K_4' , the join K_1 is underlined and shown in blue. Top right: the list of snapshots before the arbitrary jump. Bottom: the execution path from K_5 to K_4' . Steps with the *step-back* and *step-back-compensate* rules are shown as \xleftarrow{r} .

```

1 Require the current program state  $K_m$  and the target program state  $K_n$  and the snapshot
list  $S^*$ .
2  $K_{join} \leftarrow \text{find\_join}(K_m, K_n)$ 
3 while  $\text{dbg}_{current}[K] \neq K_{join}$  do
4    $\text{dbg}_{current} \xleftarrow{r} \text{dbg}_{next}$ 
5    $\text{dbg}_{current} \leftarrow \text{dbg}_{next}$ 
6 while  $\text{dbg}_{current}[K] \neq K_n$  do
7    $\text{dbg}_{current} \xleftarrow{d,i} \text{dbg}_{next}$ 
8    $\text{dbg}_{current} \leftarrow \text{dbg}_{next}$ 

```

Algorithm 5-1. The algorithm for traveling to any position in the multiverse tree.

Figure 5-10 illustrates the algorithm for jumping to an arbitrary state, when the user clicks on a node on another branch in the multiverse tree. The figure shows a possible multiverse tree for a program where the second and third instruction are input primitives. The program has executed two input primitives in a row, and the debugger has explored some of the possible inputs. Each node in the figure is labeled with the program state and possible compensating action, where r_{nop} indicates that no compensating action is needed. For clarity, the external states are also numbered. The figure shows clearly that the external state only changes after a primitive call. The current state is K_5 , and the debugger wants to jump to K_4' . Per the algorithm, the debugger finds the join of the two states, which is K_1 . The debugger then replays the execution from K_5 to K_1 in reverse order, using the *step-back* and *step-back-compensate* rules. It is important that the debugger steps back one instruction at a time, to ensure that the external state is correctly restored.

From the join K_1 , the debugger replays the execution to $K_{4'}$ in the forward order, using the *step-mock* rule whenever it encounters a non-deterministic primitive call. This ensures that the jump deterministically follows the exact execution path, thereby ensuring that the external state is correctly restored.

5.3.9 Correctness of the Multiverse Debugger Semantics

Given the small-step semantics, we can prove the correctness of the MIO debugger in terms of soundness and completeness. The soundness theorem states that for any debugging session ending in a certain state, there also exists a forwards execution path in the underlying language semantics to that state. A debugging session is seen as any number of debugging steps starting from the initial debugging state $\text{dbg}_{\text{start}}$. The completeness of the debugger means that the debugger can always find a path in the multiverse tree that corresponds to a path in the underlying language semantics. Together, these properties ensure that the debugger is correct in terms of its observation of the underlying language, and will never observe any inaccessible states. For brevity, we only provide a sketch of the proofs here, but the full proofs can be found in Appendix H.

Theorem 5-1. (Debugger soundness) Let K_0 be the start WebAssembly configuration, and dbg the debugging configuration containing the WebAssembly configuration K_n . Let the debugger steps $\hookrightarrow_{d,i}^*$ be the result of a series of debugging messages, where msg is the last message. Then:

$$\forall \text{dbg} : \text{dbg}_{\text{start}} \hookrightarrow_{d,i}^* \text{dbg} \implies K_0 \hookrightarrow_i^* K_n$$

The proof for debugger soundness proceeds by induction over the number of steps in the debugging session. In the base case, where the debugging session consists of a single step, the proof is trivial since the step starts from the initial state. In the inductive case, the proof proceeds very similarly, the only non-trivial cases are those for stepping backwards and mocking.

Theorem 5-2. (Debugger completeness) Let K_0 be the start WebAssembly configuration for which there exists a series of transition \hookrightarrow_i^* to another configuration K_n . Let the debugging configuration with K_n be dbg . Then:

$$\forall K_n : K_0 \hookrightarrow_i^* K_n \implies \text{dbg}_{\text{start}} \hookrightarrow_{d,i}^* \text{dbg}$$

The proof for completeness follows almost directly from the fact that for every transition in the underlying language semantics, the debugger can take a corresponding step. For non-deterministic input primitives, we can step to the same state with the *register-mock* and *step-mock* rules.

Together the debugger soundness and completeness theorems ensure that the multiverse debugger is correct in terms of its observation of the underlying language semantics. However, it gives us no guarantees about the correctness of the compensating actions, and the consistency of external effects during a debugging session. Due to the way effects on the external environment are presented in the MIO debugger semantics, we can define the entire effect of a debugging session of regular execution, both as ordered lists of steps that have external effects. There are only two options, the output primitive rules, and the rule that applies the compensating action.

Definition 5-1. (External state effects) The function *external* returns the steps affecting external state for any series of rules in the debugging or underlying language semantics.

$$\text{external}(p) = \begin{cases} s \text{ for } s \text{ in } p \text{ where } s = \text{step-prim-out} & \text{if } p = \text{dbg} \hookrightarrow_{d,i}^* \text{dbg}' \\ \vee s = \text{step-back-compensate} \\ s \text{ for } s \text{ in } p \text{ where } s = \text{output-prim} & \text{if } p = K \hookrightarrow_i^* K' \end{cases}$$

Using this definition, we can prove that the external effects of any debugging session ending in a certain state, are the same as the effects of the regular execution of the program ending in that same state. The definition for the equivalence of external effects (\equiv) is given in Appendix H.

Theorem 5-3. (Compensation soundness) Let K_0 be the start WebAssembly configuration, and dbg the debugging configuration containing the WebAssembly configuration K_n . Let the debugger steps $\hookrightarrow_{d,i}^*$ be the result of a series of debugging messages. Then:

$$\forall \text{dbg} : \text{external}(\text{dbg}_{\text{start}} \hookrightarrow_{d,i}^* \text{dbg}) \equiv \text{external}(K_0 \hookrightarrow_i^* K_n)$$

The proof of this theorem is based on the fact that our multiverse debugger is a rooted acyclic graph, and a debugging session is a walk in this tree starting from the root, which can include the same edge several times. Any such walk in a tree can be constructed by adding any number of random closed walks to the path from the root to the final node. Such closed walks are null operations in terms of their effect on the external state. This leaves only the forward steps of the minimal path to be considered, meaning the external effects of a debugging session are always the same as those of the regular execution of the program.

5.4 The MIO debugger

We have implemented the multiverse debugger described above in a prototype debugger, called the MIO debugger. The MIO debugger is built on top of the WARDuino runtime. Our prototype implementation builds further upon the virtual machine and the remote debugging facilities described in Chapter 3. Under the hood, the virtual machine needed to be extended significantly in order to support all the basic operations for multiverse debugging: smart snapshotting, mocking of primitives and reversible actions. Additionally, we created a high-level interface which implements the message passing interface described in Section 5.3 as messages in the remote debugger of WARDuino. On top of this interface we built a Kotlin application for debugging AssemblyScript programs on microcontrollers running WARDuino. This application keeps track of the program states, and shows them as part of the multiverse tree, as shown in Figure 5-1 from Section 5.2. Algorithm 5-1 for arbitrary jumping, is implemented at the level of the Kotlin application using the message passing interface of the remote debugger. Finally, the MIO prototype also has support for expressing simple dependencies, so that the mocking of the various sensor values can be limited depending on state of the output pins.

5.4.1 Output: Reversible Primitives

Primitives in WARDuino are implemented in the virtual machine using C macros. In order to implement reversible primitives, we have extended the existing macros with two new macros; one defines how the external state effected by the primitive can be captured, and the other defines the compensating action given this captured state. When stepping back over a primitive, the compensating action looks at the state captured after the previous primitive call, and restores this external state. This is the same as undoing the effects of the last primitive call.

To illustrate the implementation of reversible primitives, we will use the example of the *rotate* primitive, which rotates a servo motor for a given number of degrees. The forwards implementation is shown on the left side of Listing 5-1. To move the motor a given number of degrees the primitive first sets the target angle of the motor encoder, this happens on Line 7. The motor encoder is used to track the current motor angle, as well as the absolute target angle, which can be set with the *set_angle* method. To rotate the motor a number of degrees relative to its current position, the primitive adds the degrees to the current motor angle (Line 8). Once the target angle is set, the primitive drives the motor to that angle using the *drive* method, as shown on Line 10.

```

1 def_prim(rotate, threeToOneU32)      1 def_prim_serialize(rotate) {
2 {                                     2   for (int m = 0; m < MOTORS; i++) {
3   int32_t speed = arg0.int32;          3     external_states.push_back(
4   int32_t degrees = arg1.int32;        4       new MotorState(m, encoders[m]-
5   int32_t motor = arg2.int32;          5         >angle()));
6   pop_args(3);                      5   }
7   auto encoder = encoders[motor];    6
8   encoder->set_angle(              7 def_prim_reverse(rotate) {
9     encoder->get_angle() +           8   for (IOState s : external_states) {
10    degrees                         9     if (isMotorState(s)) {
11  );                                10       int motor = stoi(s.key);
12  return drive(motor, encoder,        11       auto encoder = encoders[motor];
13    speed);                        12       encoder->set_angle(s.degrees);
14 }                                13       drive(motor, encoder, STD_SPEED);
14 }}}

```

Listing 5-1. *Left:* The implementation of the *rotate* primitive. *Right:* The implementation of the compensating action for the *rotate* primitive, in the MIO debugger.

The implementation of the compensating action for the *rotate* primitive is shown on the right side of Listing 5-1. First, the *def_prim_serialize* macro captures the external state. For each motor, the current angle of the motor is stored along with its index, as shown on Line 4. Second, the *def_prim_reverse* macro compensates the primitive by moving all motors back to the angles captured in the previous snapshot. The angles captured by the *def_prim_serialize* macro are absolute target angles. The compensating action moves the motors back to these angles by first setting the target angle, as shown on Line 12. It then uses the same *drive* function to move the motor.

5.4.2 Input: mocking of primitives

The input mocking is implemented analogous to the debugger semantics, by adding a map to the in the virtual machine state. This map is used to store the mocked values for the input primitives, which are received by a new debug message in the remote debugger. In line with the semantics, there is also a new debug message to remove a mocked value from the map. Currently, the map only supports registering primitive calls with their first argument. This is sufficient for the current input primitives to be mocked, without any changes to their implementation.

The virtual machine will check the map of mocked values for every primitive call. The prototype includes two input primitives that can be mocked in this way, the *digitalRead* primitive which reads the value of a digital pin, and the *colorSensor* primitive which reads a value from a UART color sensor. The

`digitalRead` primitive enables the user to mock the value of a digital pin, and thereby the behavior of a wide range of possible peripherals. However, the range of possible input values is not always known statically, as it may be influenced by the output effects of the program. To handle this, the MIO debugger includes initial support for predictable dependencies that can be defined as simple conditions, for example, “*when the value of a digital pin n is x, then input primitive p with arguments m will return the value c*”.

5.4.3 Performance: Checkpointing

To reduce memory usage, the MIO debugger only stores the snapshots at certain checkpoints. The semantics of MIO only takes snapshots after a call to a primitive, the prototype implementation follows this checkpointing policy precisely. As shown by the debugger semantics and the proof, this is the minimum number of snapshots needed to enable backwards and forwards exploration of the multiverse tree. To further reduce the performance impact on the microcontroller, snapshots are received and tracked by the desktop frontend of the MIO debugger. To have minimal traffic between the debugger backend and frontend, snapshots after primitive calls are sent automatically to the frontend. Alternatively, the debugger frontend can request snapshots at will through the remote debugger interface.

5.5 Evaluation

To validate that our checkpointing strategy is performant enough for apply multiverse debugging on microcontrollers we performed a number of experiments. All experiments were performed on an STM32L496ZG microcontroller running at 80 MHz. This microcontroller was connected to a laptop running the MIO debugger frontend that communicates with the microcontroller.

5.5.1 Forward execution with checkpointing

The first experiment evaluates the performance impact of checkpointing on the execution speed. We measured the execution time of a fixed number of instructions, when taking no snapshots, taking a snapshot every instruction, and for snapshotting after different intervals (5, 10, 50, or 100 instructions), as shown in Figure 5-11. To reduce the impact of variable unknown factors, the program executed by the virtual machine includes no primitive calls. Specifically, this program checks for each integer from 1 to 13,374,242 if they are prime. Because this program has no primitive calls, the VM will only take snapshots at fixed intervals which are determined by the frontend.

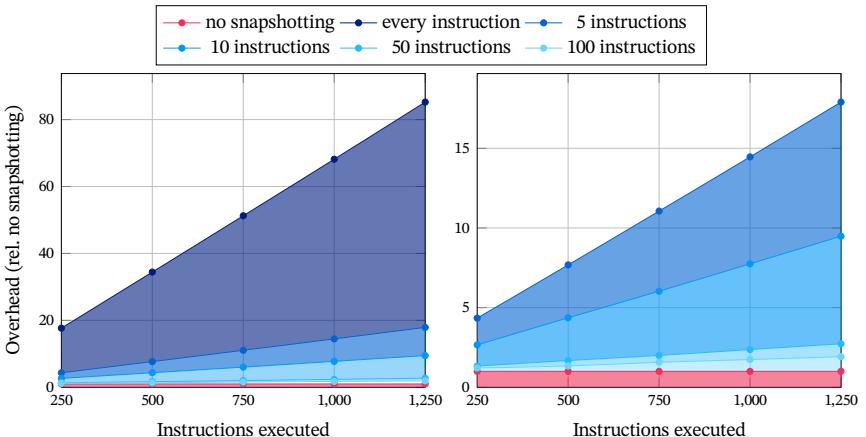


Figure 5-11. Comparison of execution time of *no snapshotting* with *snapshotting* for *every instruction*, and different checkpointing intervals; *every 5, 10, 50, and 100 instructions*. The performance overhead is shown as execution time relative to the execution time when taking no snapshots. Left: Comparison of all checkpointing policies, snapshotting, and no snapshotting. Right: Comparison of all checkpointing policies with no snapshotting. The averages are taken over 10 runs of the same program.

The left plot shown in Figure 5-11, gives the time it took to execute up to 1250 instructions for each snapshot policy relative to taking no snapshots. Since snapshotting every instruction is so much slower, we added the right plot showing the same results, but without snapshotting at every instruction. For such small numbers of instructions, the execution time without any debugger intervention, remains roughly the same, taking on average 222.7ms. These results are shown in red. In contrast, when taking snapshots after every executed instruction, the execution time increases dramatically. For 1250 instructions it takes on average 19 seconds, which is around 85 times slower. For only 250 instructions the execution time increases seventeen-fold, to 3.9 seconds.

Once checkpointing is used the overhead reduces significantly. When taking snapshots every five instructions, the virtual machine only needs 4 seconds to execute 1250 instructions. Per instruction this results in an execution that is only 17.9 times slower. Taking a snapshot every 10 instructions results in a total execution time of 2.1 seconds. This results in a slowdown of factor 9.5. When taking snapshots every 50 instructions, the slowdown lowers to a factor of 2.7. Going up to a hundred instructions every snapshot, this becomes only a factor 1.9.

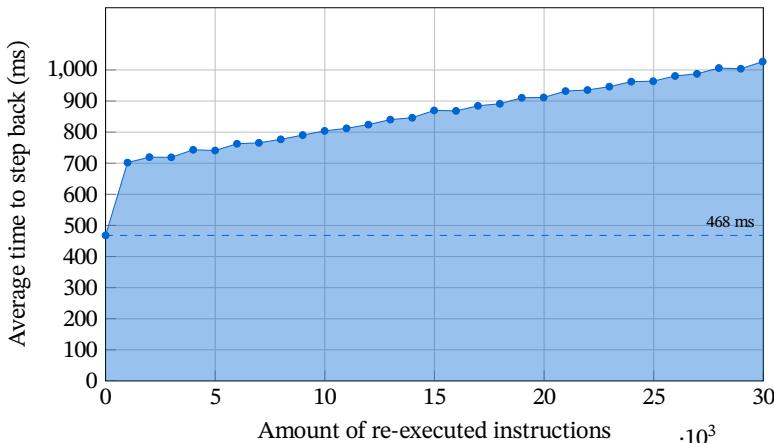


Figure 5-12. Plot showing the average time to step back as the number of instructions requiring re-execution increases in increments of one thousand. Averages are calculated over 10 runs of the same program.

This initial benchmark of the checkpointing strategy shows that the performance overhead can be greatly reduced by reducing the number of snapshots taken. Yet, execution times are still significantly slower than without any snapshotting. This is due to the fact that the current prototype has not yet been optimized for performance. The prototype only uses a simple run-length encoding of the WebAssembly memory to reduce the size of the snapshots. In future improvements, the snapshot sizes could be reduced greatly by only communicating the changes compared to the previous snapshot. However, in practice the performance is already sufficient to provide users with a responsive debugger interface as we illustrate in the online demo videos, which can be found [here](#)⁵. The example we highlight later in Section 5.5.3, requires on average snapshot every 37 instructions. This reduces overhead sufficiently to have a responsive debugging experience for users. Additionally, the I/O operations by comparison typically take much longer to execute, a single action easily taking several seconds.

5.5.2 Backwards execution

The graphs in Figure 5-11 only show part of the picture, where the less snapshots are taken, the better the performance. Unfortunately, there is no such thing as a free lunch, and while only taking one snapshot at the start of the program and never again, would result in the lowest possible overhead for

⁵Full link: <https://youtube.com/playlist?list=PLaz61XuoBNYVcQqHMAAXQNf8fz5IAMahe&si=HNrKY9YzqDFadATN>

fowards execution, this is not the case for backwards execution. In that case stepping back would always have to re-execute the entire program. Clearly, the further apart the snapshots, the longer it will take to step back. To illustrate this trade-off, we examined the impact of the number of re-executed instructions on stepping back speed.

Figure 5-12 shows the average time it takes to step back as the number of instructions requiring re-execution increases in increments of one thousand. The averages are calculated over 10 runs of the same program used in the previous section. When executing only a handful of instructions, the time to step back is dominated by the communication latency between the microcontroller and the debugger frontend. On average, this results in a minimal time of 468ms to step back. Between one thousand and 30 thousand re-executed instructions, the time to step back increases linearly by roughly 11ms per a thousand instructions.

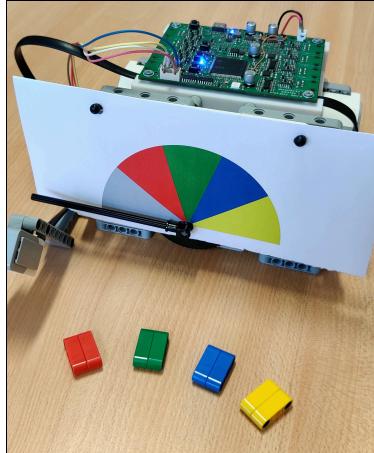
Our analysis of the checkpoint strategy's impact on stepping back shows that the overhead is minimal. The prototype is able to re-execute 30 thousand non-I/O instructions in around one second. Compared to the overhead of checkpointing on forwards execution (see Figure 5-11), we can safely conclude that in practice the overhead on backwards execution is negligible. This is further evidenced in our [demo videos](#), where developers mostly have to wait for physical I/O actions to complete, and stepping back is otherwise instantaneous.

5.5.3 Use case: Lego Mindstorms color dial

To illustrate the practical potential of MIO and its new debugger approach, we present a simple reversible robot application using Lego Mindstorms components. However, not just microcontroller applications may benefit from our novel approach, there are many application domains where output is entirely in the form of digital graphics, which are more easily reversible—such as video games, simulations, etc. Nevertheless, to highlight the potential of the approach we demonstrate the MIO debugger using small physical robots and other microcontroller applications, as this is a more challenging environment for multiverse debugging. Using the digital input and motor primitives described in Section 5.4, we developed a color dial, as a simplified application. We developed this example alongside a few others to further demonstrate the usability of the MIO debugger, and have created demo videos for a few of the examples, which can be found [online](#)⁵.

Code for all examples can be found [online](#).

The color dial application works as follows; the robot has a color sensor that can detect the color of objects. Depending on the color seen by the sensor, a single motor will move the needle on the dial to the location indicating the



```

1 enum Color { none = 0, red = 1, green = 2,
2   blue = 3, yellow = 4 }
3
4 const sensor = colorSensor(Pin.IO2);
5 let current: Color = Color.none;
6 while (true) {
7   let next: Color = sensor.read();
8   if (next != current) {
9     // turn the needle if the color changed
10    rotate(Pin.IO1,
11        (next - current) * angle, speed);
12  }
13  current = next;
14 }
```

Figure 5-13. Left: Lego color dial that recognizes the color of objects. Right: The main loop controlling the behavior of the color dial. The dial is controlled by a single motor connected to pin IO1, and the color sensor is connected to pin IO2.

color seen by the sensor. We built the dial using LEGO Mindstorms components (Ferreira Ruiz et al., 2024) as shown on the left of Figure 5-13. The right-hand side of Figure 5-13 shows the infinite loop that controls the robot, written in AssemblyScript. In this loop, the robot will continually read sensor values from the color sensor. While doing so it will move the needle of the dial to the correct position indicating the current color seen by the sensor. The needle is only moved if the color sensor sees a value different from what the dial is currently indicating. The relative amount that the needle needs to move is calculated by taking the difference between the current color the needle is pointing at and the new color.

The program for the color dial uses the reversible primitive *rotate*, used as an example in Section 5.4, to rotate the needle of the dial. By using only reversible output primitives, the program written for this robot automatically becomes reversible. This means that while debugging the application, the color the needle is pointing towards will always correspond to variable *current* in the program. Concretely, if the debugger steps back through the program from the end of a loop iteration to Line 8, it will move the needle back to the previous color without having to read a new sensor value. This makes it easy to test certain state transitions where the needle is pointing at one particular color and now has to move to a different color.

Aside from using time travel debugging which keeps external state in mind, users of our debugger are also able to leverage multiverse debugging capabil-

ties to deal with the non-deterministic nature of this color sensor. This allows them to easily simulate various sensor values, and explore the different paths the robot can take without needing to use any real, correctly-colored objects. This example touches on a few common aspects of robotics applications, such as processing non-deterministic input, controlling motors and making decisions based on sensor values. Using the I/O primitives supported by MIO, various other applications could be build; such as a binary LED counter, a smart curtain, an analogue clock, a maze solving robot, and so on.

5.6 Related work

Our work builds directly on WebAssembly (Haas et al., 2017; Rossberg, 2023, 2019) and WARDuino (Lauwaerts et al., 2024), as we have discussed in Section 5.3.3 and Section 5.4. In this section, we present an overview of further related work.

Multiverse debuggers

Multiverse debugging has emerged as a powerful technique to debug non-deterministic program behavior, by allowing programmers to explore multiple execution paths simultaneously. It was proposed by Torres Lopez et al. (2019) to debug parallel actor-based programs, with a prototype called Voyager (Gurdeep Singh et al., 2019), that worked directly on the operational semantics of the language defined in PLT Redex (Felleisen et al., 2009). Several works have expanded on multiverse debugging; Pasquier et al. (2022) introduced user-defined reduction rules to shrink the state space that must be explored during multiverse-wide breakpoint lookup, and Pasquier et al. (2023b) introduced temporal breakpoints that allow users to reason about the future execution of a program using linear temporal logic. In contrast to MIO, existing multiverse debuggers only work on a model of the program execution, and do not consider I/O operations, or their effects on the external environment.

Multiverse Analysis

The idea of exploring the multiverse of possibilities, is more widely known as multiverse analysis. Within statistical analysis, it is a method that considers all possible combinations of datasets and analysis simultaneously (Steegen et al., 2016). Within software development, there are several frameworks for exploratory programming (Kery and Myers, 2017), which allow developers to interact with the multiverse of source code versions (Steinert et al., 2012). In exploratory programming, programmers actively explore the behavior of

a program by experimenting with different code. This approach has led to *programming notebooks* (Kery et al., 2018, Perez and Granger, 2007), and dedicated *explore-first IDEs* with advanced version control (Kery and Myers, 2017, Steinert et al., 2012). Explore-first editors, such as the original by Steinert et al. (2012), allows programmers to explore different versions of their code in parallel. While explore-first editors consider the variations in the program code itself, multiverse debuggers focus on variations of program execution caused by non-deterministic behavior for a single code base. Combining these two techniques could lead to a powerful development environment, and represents interesting future work.

Exploring execution trees

Many automatic verification and other analysis tools also explore the execution tree of a program, such as software *model checkers* (Godefroid, 1997, Jhala and Majumdar, 2009), *symbolic execution* (Baldoni et al., 2018, Cadar et al., 2011, King, 1976), and *concolic execution* (Godefroid et al., 2005, Marques et al., 2022, Sen and Agha, 2006). These techniques are great at automatically detecting program faults, however, they rely on a precise description of the problem or program specification, often in the form of a formal model. This is in stark contrast with debuggers, which are tools to help developers find mistakes for which no precise formula exists, and for which the causes are often unknown. Despite the major differences, static analysis techniques could greatly help improve debuggers by providing the developers with more information. For multiverse debugging the techniques could help guide developers through large and complicated execution trees. Additionally, the techniques for handling the state explosion problem (Kahlon et al., 2009, Kurshan et al., 1998, Valmari, 1998) developed for these analysis tools, can help reduce the number of redundant execution paths in multiverse debugging.

Reversible debuggers

Reversible debugging, also called back-in-time debugging, has existed for more than fifty years (Balzer, 1969), and has been implemented with various strategies (Engblom, 2012). *Record-replay debuggers* (Agrawal et al., 1991, Boothe, 2000, Burg et al., 2013, Feldman and Brown, 1988, O'Callahan et al., 2017, Ronsse and De Bosschere, 1999) allow offline debugging with a checkpoint-based trace. In spite of all the different implementation strategies, few reversible debuggers also reverse output effects, with a few notable exceptions. The more recent RR framework (O'Callahan et al., 2017) is a culmination of many years of research, and is one of the most advanced record-replay debuggers to date. While replaying it does not reverse I/O

operations, in fact, the operations are not performed at all. For example, file descriptors are not opened during replay, but instead the external effects are recorded and replayed within the debugger. One of the earliest works, the Igor debugger (Feldman and Brown, 1988), featured so-called *prestart routines*, which could perform certain actions after stepping back, such as updating the screen with the current frame buffer. This is one of the first attempts at dealing with external state, however, the solution was purely ad-hoc, and required significant user intervention; for instance, supplying the name, mode, and file pointer for each file currently opened during execution. Additionally, dealing with I/O in a structured way through the prestart routines was still too costly at the time. There is also no proof of soundness, or any characterization of which prestart routines lead to correct debugging behavior. *Omniscient debuggers* (Lewis, 2003, Pothier et al., 2007), on the other hand record the entire execution of a program, allowing free offline exploration of the entire history, and enabling advanced queries on causal relationships in the execution (Pothier and Tanter, 2009). A third approach is based on *reversible programming languages* (Giachino et al., 2014, Lanese, 2018, Lanese et al., 2018). While not applicable in all scenarios, since it requires a fully reversible language, this approach can enable more advanced features, such as reversing only parts of a concurrent process, while still remaining consistent with the forwards execution (Lanese, 2018). The reversible LISP debugger by Lieberman (1997) not only redraws the graphical output, but also links graphics with their responsible source code. Reversible debuggers for the *graphical programming language* Scratch (Maloney et al., 2010), namely Blink (Strijbol et al., 2024) and NuzzleBug (Deiner and Fraser, 2024), also redraw the graphical output when stepping back. However, in all these debuggers, the output effects are internal to the system. For the Scratch debuggers, the visual output is actually part of the execution model (Maloney et al., 2010).

Reversible programming languages

The concept of reversible computation has a longstanding history in computer science (Bennett, 1988, Mezzina et al., 2020, Zelkowitz, 1973), with the most notable models for reversibility being reversible Turing machines (Axelsen and Glück, 2016), and reversible circuits (Saeedi and Markov, 2013). Furthermore, the design of reversible languages has evolved into its own field of study (Glück and Yokoyama, 2023), with languages for most programming paradigms, such as the imperative, and first reversible language, Janus (Lami et al., 2024, Lutz and Derby, 1986, Yokoyama et al., 2008), several functional languages (Matsuda and Wang, 2020, Yokoyama et al., 2012), object-oriented languages (Haulund et al., 2017, Hay-Schmidt et al., 2021, Schultz and Axelsen, 2016), monadic computation (Heunen and Karvonen, 2015), and

languages for concurrent systems (Danos and Krivine, 2004, Hoey et al., 2018, Schordan et al., 2016). Several works have investigated how reversible languages can help reversible debuggers (Chen et al., 2001, Engblom, 2012, Lanese et al., 2018), however, full computational reversibility is not necessary for back-in-time debugging (Engblom, 2012). Moreover, these reversible languages do not consider output effects on the external world, with a few notable exceptions in the space of proprietary languages for industrial robots.

Reverse execution of industrial robotics

While numerous examples can be imagined where actions affecting the environment cannot be easily reversed, there are sufficient scenario's where this is possible, for reverse execution to be widely used in industry. The reversible language by Schultz (2020) is particularly interesting. The work proposes a system for error handling in robotics applications through reverse execution, and identifies two types of reversibility; direct and indirect. Through our compensating actions, MIO is able to handle both directly and indirectly reversible actions. Laursen et al. (2018) propose a reversible domain-specific language for robotic assembly programs, SCP-RASQ. While we do not focus on a single specific application domain, this work does show how reversible output primitives are possible for advanced robotics applications. SCP-RASQ uses a similar system of user-defined compensating actions, to reverse indirectly reversible operations. Using these kinds of languages, we believe that the MIO debugger could be extended to support more complex output primitives, which could control industrial robots.

Reversibility

The concept of reversibility is well understood on a theoretical level, for both sequential context (Leeman, 1986), and concurrent systems. The latter is much more complex, and has lead to two major definitions; causal-consistent reversibility (Danos and Krivine, 2004, Lanese et al., 2014), and time reversibility (Kelly, 1981, Weiss, 1975). Causal-consistent reversibility is the idea that an action can only be reversed after all subsequent dependent actions have been reversed (Lanese et al., 2014). This ensures that all consequences of an action have been undone before reversing, and the system always returns to a past consistent state. On the other hand, time reversibility only considers the stochastic behavior when time is reversed (Bernardo et al., 2023, Kelly, 1981, Weiss, 1975). However, it has recently been shown that causal-consistency implies time reversibility (Bernardo et al., 2023). Our debugger works on a single-threaded language, where the non-determinism is introduced by the input operations. In our work, the undo actions are causally consistent in the single-threaded world. We believe that we can extend MIO

to support concurrent languages, and that the existing literature (Giachino et al., 2014, Lanese et al., 2018) can help to ensure it stays causally consistent.

Remote debugging on microcontrollers

We discussed the related work on remote debuggers for embedded devices thoroughly in Section 3.11. The MIO multiverse debugger is built on top of the same architecture as *stub remote debuggers*.

Environment modeling

There are many environment interactions that can influence the possible input values and thereby the possible execution paths of a program. We have elided these interactions from the formal model and assume that I/O operations are independent, while our prototype does support defining simple *predictable dependencies* between I/O operations. Modeling the interactions between I/O operations is also hugely important for testing, and *environment modeling* has therefore been widely studied in this area (Blackburn, 1998). Environment models are often used for automatic test generation (Auguston et al., 2005, Dalal et al., 1999) for a certain specification, and have also been applied to real-time embedded software (Iqbal et al., 2015).

5.7 Conclusion

While existing multiverse debuggers have shown promise in abstract settings, they struggled to adapt to concrete programming languages and I/O operations. In this article, we address these limitations by presenting a novel approach that seamlessly integrates multiverse debugging with a full-fledged WebAssembly virtual machine. This is the first implementation that enables multiverse debugging for microcontrollers. Our approach improves current multiverse debuggers by being able to provide multiverse debugging in the face of a set of well-defined I/O actions. We have formalized our approach and give a soundness and completeness proofs.

We have implemented our approach and have given various examples showcasing how our approach can deal with a wide range of specialized I/O actions, ranging from non-deterministic input sensors, to I/O pins and even steering motors. Our sparse snapshotting approach delivers reasonable performance even on a restricted microcontroller platform. While the MIO debugger is already sufficiently fast, it is currently implemented as a remote debugger. We can likely speed-up performance by adopting stateful out-of-place debugging we introduced in the previous chapter.

Conclusion

Our initial implementation provides a substantial benefit over existing approaches, but we believe there are further opportunities to relax the constraints on I/O actions further. For example, our current implementation only supports simple dependencies between I/O actions, but we believe this could be relaxed further by introducing an explicit rule language so that programmers can define more complex dependencies between the I/O actions.

Chapter 6

Managed Testing

If you know the way broadly, you will see it in everything.

— Miyamoto Musashi, *The Book of Five Rings*

Debuggers are only useful when you know you have a bug. There are naturally many ways to discover bugs in your software, however, the single most effective and widely used approach is unsurprisingly *testing*. Modern software uses continuous integration and regression testing to detect bugs as early as possible in the development cycle.

Unfortunately, the same reasons that cause debugging techniques to lag behind for embedded devices, likewise make modern testing techniques hard to apply on constrained systems. In this chapter, we present a novel testing technique called *managed testing*, and a prototype implementation Latch, which aim to enable large-scale testing of embedded software directly on the constrained devices as part of continuous integration. The framework was also used to test the previously discussed debugger prototypes.

6.1 Introduction

Software testing for constrained devices, still lags behind standard best practices in testing. Widespread techniques such as automated regression testing and continuous integration are much less commonly adopted in projects that involve constrained hardware. This is mainly due to the heavy reliance on physical testing by Internet of Things (IoT) developers. A 2021 survey on IoT development found that 95% of the developers rely on manual (physical) testing (Makhshari and Mesbah, 2021). Testing on the physical hardware poses three major challenges, which hinder automation and the adoption of modern testing techniques. First, the *memory constraints* imposed by the small memory capacity of these devices makes it difficult to run large test suites. Second, the *processing constraints* of the hardware causes tests to execute slowly, preventing developers from receiving timely feedback. Third, *timeouts and flaky tests* pose a final challenge. When executing tests on constrained hardware it is not possible to know when a test has failed or is simply taking too long.

To circumvent the limitations of constrained hardware, simulators are sometimes used for testing IoT systems (Bures et al., 2020). Their usage makes adopting automated testing and other common testing practices much easier. Unfortunately, simulators can never fully capture all aspects of real hardware (Espressif Systems, 2023a, Khan et al., 2011, Roska, 1990). Therefore, to fully test their applications, IoT developers have no other option than to test on the real devices. This is the primary reason why developers still prefer physical testing. Another reason is the lack of expressiveness when specifying tests in automated testing frameworks. Testing frameworks with simulators almost exclusively focus on unit testing, and hence provide no good alternative to end-to-end physical testing performed by developers manually (VanderVoord et al., 2015).

In this chapter, we argue that programmers should not be limited by either the constraints of the hardware, or a simulator imposed by the testing framework. Therefore, our goal is to design and implement a testing framework for automatically running large-scale versatile tests on constrained systems. This has lead to the development of the *Latch* testing framework (Large-scale Automated Testing on Constrained Hardware). *Latch* enables programmers to script and run tests on a workstation, which are executed on the constrained device. This is made possible by a novel testing approach, we call *managed testing*. In this unique testing approach, the test suite is split into small sequential steps, which are executed by a testee device under the directions of a controlling tester device. The workstation functions as the tester which maintains full control over the test suite. Only the program under test—not the entire test suite—will be sent to the constrained device, the testee. The tester will use instrumentation to manage the testee and instruct it to perform the tests step-by-step. This means the constrained testee is not required to have any knowledge of the test suite being executed. This is quite different from traditional remote testing, where the entire test suite is sent to the remote device. The instrumentation of the testee is powered by debugging-like operations, which allow for traditional whitebox unit testing, but also enables the developer to write debugging-like scripts to construct more elaborate testing scenarios that closely mimic manual testing on hardware.

The research question we seek to answer in this chapter, is whether the managed testing approach, i.e. splitting tests into sequential steps, is sufficient for executing large-scale tests on microcontrollers. To answer this question, we will show how managed testing allows *Latch* to overcome all three major challenges of testing on constrained devices. The approach can be summarized as follows. In *Latch* test suites are split up into smaller test instructions that are sent incrementally to the managed testee, thereby freeing the test suites from the *memory constraints* of the hardware. This is crucial in enabling large-scale test suites on microcontrollers, such as

the large unit testing suite containing 10,213 tests we use to evaluate our approach. To overcome the *processing constraints*, *Latch* can skip tests that depend on previously failing tests resulting in a faster feedback loop. Finally, *Latch* handles *timeouts* automatically, and includes an analysis mode which reports on the *flakiness of tests*.

6.1.1 Contributions

- We define a test specification language for writing large tests suite for constrained devices.
- We develop the *Latch* framework, that implements the test specification language as an embedded domain-specific language (EDSL).
- We present a novel testing methodology based on debugging methods, that allows common manual testing of code on hardware to be automated.
- We illustrate how *Latch* can be used to address testing scenarios from all three layers of the testing pyramid (Cohn, 2009).
- We evaluate *Latch* by using it to run 10,213 unit tests on an ESP32 microcontroller.

The rest of the chapter starts with a discussion of the challenges of testing on constrained device in Section 6.2. In Section 6.3 we give a first introduction to the *Latch* test specification language through a basic example, and use the example to give an overview of the *Latch* framework. We discuss the details of the language in Section 6.4, and focus on how tests are written and executed by the framework. For each aspect of the test specification language we discuss how it helps *Latch* to address the challenges outlined previously. We conclude the section by briefly touching on the prototype implementation. Section 6.5 further illustrates how *Latch* can be used to handle different testing scenarios, and can help testers implement a range of testing methodologies. We discuss three scenarios, classic large-scale unit testing, integration testing, and automating physical end-to-end testing using the debug-like operations provided by *Latch*. In Section 6.6 we evaluate the runtime performance of *Latch* based on a variety of test suites, and present empirical evidence that managed testing enables large-scale automatic testing on constrained hardware. In Section 6.7 we discuss the related works, before concluding in Section 6.8.

6.2 Challenges of Testing on Constrained Devices

This section outlines the challenges preventing large-scale testing on constrained hardware.

ESP32 devices can have different amounts of memory, but the order of magnitude is the same.

6.2.1 Memory Constraints

In this chapter, we focus on the ESP32 microcontroller family having about 400 KiB SRAM and 384 KiB ROM, typically operating at a clock frequency around 160-240 MHz. Due to these hardware limitations, programs cannot be arbitrarily large as the program memory is quite small and they execute slower than workstations. For companies producing IoT devices it is often desirable to make use of the cheapest and most minimal hardware possible that can handle the task at hand. This means that when executing on the hardware, there are often very few resources to spare, which limits the ability to test the applications on the device.

When test suites become large, executing these test suites on the hardware is often not possible because the compiled binary is too big to fit in the program memory of the microcontroller. The only option then is to split the test suite into smaller parts which can fit on the device. Current testing frameworks, however, do not provide automated support for splitting large test suites and executing them incrementally on the hardware. Programmers who want to execute large test suites thus have to manually partition the test suite, execute the test on the hardware, read out the results and process the dump of the individual parts.

Finally, even when the testing framework supports partitioning of the test suite reflashing the hardware for every partition is quite time-consuming. To change the program executing on the hardware the programmer needs to flash the microcontroller, i.e. write the program in the ROM partition of the microcontroller. Depending on the microcontroller, synchronization and flashing of a new program can take several seconds making it undesirable to flash the microcontroller often.

6.2.2 Processing Constraints

When relying on regression testing, the programmer wants a tight feedback loop. Ideally, the entire test suite is run after each change, but this requires feedback to be reported quickly. However, by testing on constrained devices, executing the test suite can take a lot of time, slowing down the software development cycle significantly. To provide feedback as early as possible, the framework should catch failures early. This can take many forms, but in essence a failure of any kind during a test should be visible to the developer as soon as possible. Additionally, to avoid spending time on tests that cannot succeed, the framework should run as few of these tests as possible.

Finally, when multiple hardware testbeds are available it should be easy for the developer to run tests in parallel to speed up testing. The same facilities for

scheduling and parallelization options available for unconstrained devices, should be integrated into testing frameworks for constrained devices.

6.2.3 Timeouts and Flaky Tests

Due to the limited memory and processing power of constrained devices, large test suites need to be split up in smaller chunks. Moreover, the results of the test need to be communicated with a test machine and combined. Unfortunately, this approach implies that test engineers suddenly need to take into account many of the problems associated with distributed computing.

First, when the test machine is waiting for a response, it cannot reliably distinguish between a failure or a delayed response. Many other testing frameworks need to deal with this problem, especially JavaScript frameworks (Flanagan, 2020) where asynchronous code is prevalent (Fard and Mesbah, 2017). These frameworks time out tests that take too long. Unfortunately, the fact that a test timed out does not provide much information for developers, especially when a test includes multiple asynchronous steps.

Second, the non-determinism of the asynchronous communication also contributes to an inherent problem of testing: flaky tests (Lam et al., 2019). These are tests that can pass or fail for the same version of the code. Unfortunately, on constrained hardware, many tests have the potential to become flaky due to the inherent non-determinism of these systems. For example, when testing communication with a remote server small changes in the communication timing with the server could lead to different behavior.

6.3 Managed Testing with *Latch* by Example

To overcome the outlined challenges, *Latch* uses a unique testing approach that consists of declarative test specification language to describe tests, and a novel test framework architecture to run tests. We refer to our new approach as *managed testing*. In managed testing, the testing framework runs on a local machine and delegates tests step-by-step to one or more external platforms, which are running the software under test. To facilitate this approach, tests must be easily divisible into sequential steps. That is why *managed testing* specifies tests in a declarative test specification language, where tests are described as scenarios of incremental steps. In this section we give a first overview of how managed testing in *Latch* works through an example, before going into further detail in Section 6.4. The example is chosen as a small primer on how programmers can write traditional unit tests with *Latch*'s test specification language.

```
1 export function mul(x: f32, y: f32): f32 {  
2     return x * y;  
3 }
```

Listing 6-1. A `mul` function that multiplies its two arguments, written in AssemblyScript.

```
1 const multiplicationTest: Test = {  
2     title: "example test",  
3     program: "multiplication.ts",  
4     steps: [  
5         title: "mul(6,7) = 42",  
6         instruction: invoke("mul", [WASM.f32(6), WASM.f32(7)]),  
7         expect: returns(WASM.f32(42))  
8     ]  
9 };
```

Listing 6-2. A *Latch* scenario defining a unit test for the `mul` function.

6.3.1 The Example

We define a unit test that verifies the correctness of a function for 32-bit floating point multiplication, shown in Listing 6-1. All example programs are written in AssemblyScript (The AssemblyScript Project, 2023), one of the languages supported by *Latch*'s current microcontroller platform.

Listing 6-2 shows a simple test in *Latch* containing one unit test for the target program in Listing 6-1. *Latch*'s declarative test specification language is implemented as an embedded domain specific language (EDSL) in TypeScript (Microsoft, 2023). Test scenarios are presented in *Latch* as TypeScript objects that have a title, the path to the program under test, and a list of steps. These steps make up the test scenario, and will be performed sequentially. Each step performs a single instruction, and can perform several checks over the result of that instruction.

The example performs only a single instruction, it requests that the `mul` function is invoked with the arguments 6 and 7 (see Line 6). These arguments are first passed to the `WASM.f32` function, to indicate the expected type in *AssemblyScript*. On Line 7, the example specifies that the function returns the number 42. Usually, the instruction and expectations for a step are described as objects, but *Latch* provides a handful of functions to construct these objects for common patterns—such as `invoke` and `returns`. This makes test scenarios less verbose, and quicker to write. We go into further detail on the structure of the `instruction` and `expectation` objects in Section 6.4.

```
1 const suite = latch.suite("Example test suite");
2 suite.testee("wrover A", new ArduinoSpec("/dev/ttyUSB0", "esp32:esp32:esp32wrover"),
5000)
3     .testee("wrover B", new ArduinoSpec("/dev/ttyUSB1", "esp32:esp32:esp32wrover"))
4     .test(multiplicationTest);
5 latch.run([suite]);
```

Listing 6-3. *Latch* setup code to run the multiplicationTest on two ESP32 devices.

Similar to other testing frameworks, *Latch* allows test scenarios to be grouped into test suites. Crucially, the test suites in *Latch* have their own set of testee devices, on which they will be executed. When writing a new test suite in *Latch*, programmers need to add at least one testee to the suite. Such testees can range over a wide variety of microcontrollers, as well as local simulator processes. Each platform may differ in how software is flashed, or communication initialized and performed. These platform specific concerns are captured by a single TypeScript class, Testee. Each connection with a constrained device is represented by an object of such a class. In Listing 6-3 for instance, we use the Arduino platform to connect to an ESP32 over a USB port, as shown on [Line 2](#). Users can add their own platforms by defining new subclasses of the Testee class, which can handle the specific communication requirements of the new platform.

Aside from testees, a test suite also requires test scenarios to execute. The example multiplication test is added to the test suite on [Line 4](#), before the suite is given to *Latch* to be run on [Line 5](#).

Listing 6-3 shows how a test suite is built in *Latch* through a fluent interface (Xie, 2017), meaning the methods for constructing a test suite can be chained together. Each test suite in *latch* is entirely separate from the rest, and therefore contains only its own tests, and platforms to run those tests on. In the example, two ESP32 devices are configured for the test suite. This means that when the test suite is started with the *run* function on [Line 5](#), the framework will execute all scenarios in the suite on all configured platforms. Alternatively, the user can configure *Latch* to not execute duplicate runs, but instead to split the tests into chunks that are performed in parallel on different devices. In that case, each test is only run once and the execution time of the whole test suite should be dramatically improved due to the parallelization.

6.3.2 Running the Example on the *Latch* Architecture

To run the above testing scenario on a remote constrained device, the test is loaded into *Latch* on the local unconstrained device, the *tester*. During testing, the *tester* manages one or more *testees* (constrained devices) to execute

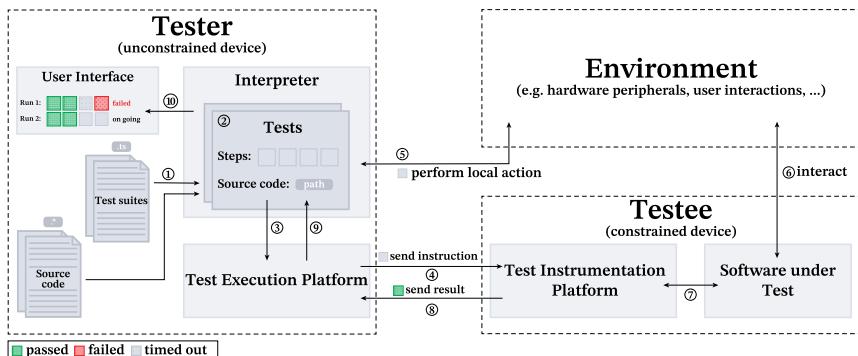


Figure 6-1. Schematic overview of the interaction between components in *Latch* during a test.

tests step-by-step. Figure 6-1 gives an overview of all steps and components involved during testing in the *Latch* framework. The left-hand side shows the tester, which runs the *Latch interpreter* and *test execution platform*. The interpreter component is responsible for interpreting the test suites, which are written in the *test specification language*, while the test execution platform sends each instruction in a test step-by-step to the testee device over the available communication medium. The test execution platform also parses the result, and handles all other aspects of communication with the testee device.

We will go over the steps shown in Figure 6-1 in the order they are executed by *Latch*. Running a test suite is initiated by the interpreter, which takes the test suite specification ①, and schedules the *scenarios* ②. Since the example test suite in Listing 6-3 only contains a single test scenario, the multiplication test, with a single step—the scheduling is not relevant in this case. In real test suites, the order in which tests are run is important, it can help detect failing tests early, or minimize expensive setup steps. When the interpreter selects a test to be executed, it will instruct the test execution platform ③ to first upload the *software under test*, and subsequently sends the instructions of the scenario to the *test instrumentation platform* ④. In the case of our example, *Latch* compiles the *multiplication.ts* file and uploads it to the ESP32 device that is connected to the USB port. Once this step is completed, *Latch* sends the invoke instruction to the testee, which will execute the *mul* function with the supplied arguments.

Aside from forwarding instructions to the test instrumentation platform, the tester can also perform custom actions to control the *environment* ⑤. For

```
1 const sendMQTT: Step = {
2   title: "Send MQTT message",
3   instruction: simpleAction((): void => {
4     let client: mqtt.MqttClient = mqtt.connect("mqtt://test.mosquitto.org");
5     client.publish("parrot", "This is an ex-parrot!");
6   })
7 };
```

Listing 6-4. An example *Latch* step, which performs a custom action that sends an MQTT message to a server.

instance, these actions can control hardware peripherals, such as sensors and buttons, that interact with the constrained testee ⑥ during the test.

Listing 6-4 shows how a step might send an MQTT message to a server as an example of an action that acts on the environment. Such a step, could be useful when testing an IoT application that relies on MQTT messages. The microcontroller can connect to an actual testing server, and via custom actions *Latch* can test if the device responds correctly.

In contrast with Listing 6-2, this example constructs the instruction object explicitly, rather than calling a function such as *invoke*. There are two types of instructions, they can be either a *request* to the test instrumentation platform, such as the invoking of a function, or a custom *action*. In this example we construct a simple action that takes no arguments and returns nothing. Actions allow tests to execute TypeScript functions as steps in the test scenario, in this case the function simply publishes a test message to the MQTT server (Line 5). We go into further detail on the types of actions and requests in Section 6.4.

As tests are performed, the software under test is controlled by the test instrumentation platform in accordance with the *request* instructions send by the test execution platform ⑦. In other words, the test instrumentation platform will receive the command from the tester to execute the *mul* function, and make the software under test invoke it. The instrumentation of the software under tests, allows the test instrumentation platform to return any generated output to the test execution platform ⑧. Whenever the tester sends an instruction to the testee, *Latch* will wait until the testee returns a result for the instruction. When working with constrained devices, communication channels may be slow or fragment messages. *Latch* takes care of these aspects automatically.

As part of a step, the scenario description can specify a number of assertions over the returned results. In the example, we require that the *mul* function returns 42, as specified on Line 7 of Listing 6-2. Once the expected output is

received by the tester, *Latch* checks all assertions against it. These assertions are verified by the interpreter ⑨, before the result of the step is shown in the *user interface* as either passed, failed, or timed out ⑩. For example, after the test instrumentation platform returns the result of the *mul* function, *Latch* will check if it indeed equals 42 and report the result.

A step can have three kinds of results; either it timed out, or all its assertions passed, or one of more assertions failed. In other words, step is marked as failing when at least one assertion fails. If no assertions were included in the step, *Latch* will not wait for output, and immediately report the action as passing. When the testee fails to return a result after a preconfigured period, it is marked as timed out. Similarly, a scenario is marked as failing when at least one step fails. When a step fails, the test execution platform will—by default—continue the scenario without retrying the step. This is useful when the steps in the scenario are independent of each other to gather more complete feedback. Otherwise, developers can configure *Latch* to abort a scenario after the first failure.

The results of each step are reported while the test suite is executing. When the entire suite has run, *Latch* will give an overview of all the results for both the steps and the test scenarios. This overview includes, the number of passing/failing tests, the number of passing/failing steps, the number of steps that timed out, and the overall time it took to run the suite. In addition, the developer can configure *Latch* to report on the flakiness of the test by executing the tests multiple times. This way, *Latch* can compare the results of different runs to give developers more insight into the flakiness of their test suites. As Figure 6-1 shows under the user interface component, the results in this case will be reported for each run separately. Whenever the runs give different results, the scenario is marked as flaky and the failure rate is reported.

6.3.3 From Small Examples Towards Large-scale Test

The running example in this section illustrates *Latch*'s basic testing features. In particular, how *Latch* divides tests into small steps that are executed sequentially. This means that the size of the test suite is no longer constrained by the memory size of the embedded device. While the example here only includes a single step, one can easily imagine test cases that require many more steps. Let us suppose we stay within the realm of unit testing a mathematical framework. We can imagine a more complicated mathematical operation than multiplication that requires thorough testing, for instance a function *eig* for calculating the eigenvalues of a matrix. In this case the test scenario would include many steps, that each invokes the *eig* function with

a different matrix. This is similar to the large-scale unit testing suite we will discuss in Section 6.5, and those run as part of the evaluation in Section 6.6.

Section 6.5 discusses realistic examples for each layer of the testing pyramid; unit testing, integration testing, and end-to-end testing. The examples will illustrate how using small steps powered by debugging-like operations, uniquely enables *Latch* to test remote debuggers and automate IoT scenarios and manual hardware tests. For example, it becomes much easier to test whether a microcontroller successfully receives asynchronous messages from a remote server, and handles these message correctly. The test can set breakpoints in the code that is expected to be executed when a message arrives. Before sending the message, the test can pause the execution at the exact place in the program, it wants the message to be received. The *Latch* instructions allows users to write these kinds of testing scenarios in a convenient way. Moreover, the increased control over the program, makes the test scenarios much easier to repeat reliably under the same conditions.

6.4 The *Latch* Test Specification Language

Latch tests are written in a declarative test specification language embedded in TypeScript. This EDSL allows developers to specify what tests should be performed, while hiding the complexity of communicating with the constrained testing device. Equally important are the debug-like commands provided by the language, which make it easier to automate hardware testing scenarios. *Latch* tests can be viewed as scripted scenarios of sequential operations. The programmer can specify what the result of executing an operation should look like, instead of manually testing whether the returned value is consistent with the expected result. For more complex tests the programmer can write test-specific evaluation functions to check whether the program behaves as expected.

The test specification language consists of four major abstractions: a test, a testing step, test instructions, and assertions. Each test includes a name, some start-up configuration and the testing steps which need to be executed during the actual test. Each testing step specifies an instruction that needs to be executed. There are two types of instructions, commands and actions. The commands are debug-like operations that are send directly to the test instrumentation platform of the testee, such as invoking a method, pausing the program, etc. Alternatively, there is support for user-specified instructions called actions. These actions allow programmers to implement their own logical and physical interactions with the hardware or the environment.

```
1 interface Test {  
2     title: string;  
3     program: string;  
4     steps: Step[];  
5     dependencies?: Test[];  
6     initialBreakpoints?: Breakpoint[];  
7 }
```

Listing 6-5. Interface for *Latch* tests. Each test has a title, indicates a program to be tested, and lists the steps to executed.

```
1 interface Step {  
2     readonly title: string;  
3     readonly instruction: Command<any> | Action<any>;  
4     readonly expect?: Assertion[];  
5 }
```

Listing 6-6. A step has a name, a specific command or action it should perform, and a possibly list of assertions to check.

The interface of a test, shown in Listing 6-5, consists of a title, the path to the program to load on the testee device, a set of initial breakpoints to halt execution, a list of dependent test, and a set of steps to be executed during the test. Both the initial breakpoints and dependent tests are optional, as indicated by the question mark after their identifier.

Testing steps all adhere to the *Step* interface shown in Listing 6-6. Each step should minimally have a title and specify which instruction to perform when executed. A step only contains a single instruction, and all steps are executed synchronously. As part of a step, the result of executing an instruction can be verified by means of assertions.

An instruction in *Latch* is either a command, or an action. Both instruction types are annotated with their return type, this is the type of the object passed to each assertion of the step. The list of assertions is optional, a step without any assertions will always succeed and immediately go to the next step.

6.4.1 Default Commands in *Latch*

The set of commands *Latch* supports is shown in Table 6-1. We divide the set of commands in intercession, meta, and introspection commands. The intercession commands, allow *Latch* tests to intervene directly with the software under test. With *invoke* the programmer can call a function and wait for the result, as illustrated by the step in our multiplication example (Listing 6-2). This enables unit testing of specific functions, as is the popular approach

Category	Commands
Intercession	invoke, set local, <i>upload module</i>
Meta	pause, set breakpoint, continue, delete breakpoint, step, step over, <i>reset</i>
Introspection	core dump, dump callback mapping, dump locals

Table 6-1. The *Latch* commands. Internal commands are in italic.

adopted in most testing frameworks (The JUnit Team, n.d., Python Software Foundation, n.d.). With *set local* the programmer can change a local variable, this is especially useful to test a program with local boundary conditions without having to rerun the program completely.

The *reset* and *upload module* instructions are primarily for internal use in *Latch*, but are available in the test specification language. The *upload module* instruction loads a binary onto the testee, replacing any current program. The *reset* instruction restarts the current program.

The meta instructions allow the programmer to install a debugging scenario by setting breakpoints and running the program to a particular point in the execution. These are especially useful for automating manual hardware tests, where different steps and events often need to happen in very specific orders. By controlling the execution of the program, these kinds of scenarios can be replicated accurately each time.

Finally, the introspection commands allow the programmer to inspect the current state of the program. Without these commands, *Latch* test would be limited to testing black boxes, since the software under test is executed on a different device. Thanks to the introspection commands, *Latch* supports black box as well as white box tests.

The proposed set of commands are inspired by standard debugging instructions, and focus on enable standard unit testing, as well as automation of manual hardware tests. Since the test specification language is embedded in TypeScript, the set of commands is easily extended by the user. Other debugging instructions could similarly inspire new *Latch* commands, such as run until, setting of conditional breakpoints, exception breakpoints, or inspecting memory addresses. Instructions tailored to asynchronous tests, such as awaiting an event, or waiting for a given time, would likewise be good additions. A new command has to implement the interface shown in Listing 6-7. A command is identified by the test instrumentation platform by its type, examples include pause, set breakpoint, and step. These commands can optionally take a payload, such as a breakpoint address for example,

```
1 export interface Command<R> {
2   type: Interrupt, // type of the debug message (pause, run,
3   step, ...)
4   payload?: (map: SourceMap.Mapping) => string, // optional payload of the debug
   message
5   parser: (input: string) => R // the parser for the
   response
6 }
```

Listing 6-7. Commands are distinguished by type and may have callback to access payload. Results are extracted by a parser.

and each command has its own parser to interpret the response of the test instrumentation platform.

By taking inspiration from debugging instructions, managed testing permits for a wide range of automated tests to be implemented, which would otherwise require additional engineering efforts in existing unit testing frameworks. Additionally, we have found that it provides a very natural way of writing tests for constrained devices. We illustrate both these points by discussing in-depth examples for each layer of the testing pyramid in Section 6.5.

6.4.2 Custom Actions in *Latch*

Aside from these commands, *Latch* allows steps to perform custom actions. These custom actions enable developers to execute arbitrary code as part of a step in the testing scenario. This is useful for interacting with the environment when testing the firmware of hardware components. Listing 6-8 shows the interface for a custom action. An action is an object with a single act field, containing a function that takes a Testee argument and returns a promise. The testee argument is provided at runtime by the *Latch* framework, to provide custom actions with access to the test instrumentation platform. This is useful to define actions that need to respond to changes on the testee device, for instance waiting for a breakpoint to be hit. Actions may be asynchronous and therefore return promises. A promise is the standard mechanism for managing asynchronicity in JavaScript and TypeScript (Madsen et al., 2017, Parker, 2015). If the action is expected to return a response, the promise should contain the output. For *Latch* to run checks over this output, it needs to be of the *Assertable* type. *Latch* provides a function that can turn any object into an *Assertable* object.

In Section 6.3 we briefly showed a simple action in Listing 6-4. However, this action returned no result, over which the test step could define assertions. Listing 6-9 gives an second example of an action that does return a result.

```
1 type Assertable<T extends Object | void> = {[index: string]: any};  
2  
3 interface Action<T extends Object | void> {  
4     act: (testee: Testee) => Promise<Assertable<T>>;  
5 }  
6  
7 declare function assertable<T extends Object>(obj: T): Assertable<T>;
```

Listing 6-8. *Latch* actions allow developers to execute arbitrary code in a test step. Output of such actions can be checked for correctness with the *Assertable*<T> interface.

```
1 function listen(topic: string): Action<Message> {  
2     let client: mqtt.MqttClient = mqtt.connect("mqtt://test.mosquitto.org");  
3  
4     return {  
5         act: () => new Promise<Assertable<Message>>((resolve) =>  
6             client.on("message", (_topic: string, payload: Buffer) => {  
7                 if (topic === _topic)  
8                     resolve(assertable({topic: topic, payload:  
9                         payload.toString()}));  
9             }))}; }
```

Listing 6-9. An example of a pure action that listens for the next MQTT message to a specific topic.

The action will listen for the next MQTT message for a specific topic. On Line 5, the act function returns a promise that resolves when the first message for the correct topic arrives. The promise contains the MQTT message of the application-specific *Message* type, including a topic and payload field. This object can be used to define checks over the payload of the message with *Latch* assertions. However, for *Latch* to run checks against the message, the returned object must conform to the *Assertable* interface. That is why on Line 8, the message object is wrapped in a *Assertable* by the assertable function, shown in Listing 6-8.

6.4.3 Assertions over instruction results

Aside from the instruction, each step contains a list of zero or more assertions. These assertions are used to perform checks on the result of the step's instruction. The result of an instruction is always of the *Assertable* type shown in Listing 6-10, which is an object that contains any number of properties that are indexed by strings.

```
1 interface Assertion { [index: string]: Expect<any>; }
2
3 type Expect<T> = T | Behaviour | (value: T) => boolean;
4
5 enum Behavior { unchanged, changed, increased, decreased }
```

Listing 6-10. Instructions return their results as *Assertable* objects. In Latch tests specify assertions over the arbitrary properties of these *Assertable* result.

For each string-indexed property of an *Assertable* result, a test step can contain one or more assertions. The interface of the assertions is shown in Listing 6-10. The Assertions represent a check over a single property of the assertable object, specified by their string index. The assertions over the object's properties follow the *Expect* interface, also shown in Listing 6-10. An *Expect* object represents an assertion over an object property of the result, and takes a type parameter *T* that should correspond with the type of that property. The *Expect* interface can be used to check for a value of type *T*, or a behavior encoded by the *Behavior* enum also shown in Listing 6-10. Behaviors can check for an unchanging, changing, increasing, or decreasing value. If these options do not suffice, developers can write their own custom checks. These are written as comparison functions that take the actual resulting value from the test, and return a boolean indicating whether the check passes.

The interface for assertions is implemented in TypeScript using a discrimination union, which is a design pattern used to differentiate between union members based on a property that the members hold. For brevity, we have omitted this detail in Listing 6-10 and all examples that follow.

The introspection commands are particularly interesting for assertions, since they enable assertions over the internal state of the testee. Consider the core dump command which returns a state object, shown in Listing 6-11 shows the dump command, which returns a state object.

For example, the dump command allows a step to check whether the testee is paused in a particular function. Listing 6-12 shows how you might write this test step. Line 4 adds two assertions to the step. The first checks whether the mode field in the state is set to pause, and the second checks if the current function has the correct name.

With the test specification language, developers can declaratively describe tests independently of the platform they should be executed on. By embedding the domain-specific language in TypeScript, we can use the type system of TypeScript to type all the constructs in the EDSL and catch mistakes in tests early.

```
1 const dump: Command<State>;
2
3 interface State {
4     line: number; // current line position
5     column: number; // current column position
6     mode: Mode; // execution mode
7     func: string; // current function
8 }
```

Listing 6-11. The *core dump* command returns a state object, which contains the source location, execution mode, and name of the currently executing function.

```
1 const step: Step = {
2     title: "CHECK: entered *echo* function",
3     instruction: Command.dump,
4     expect: [{mode: Mode.PAUSE}, {func: "echo"}]
5 }
```

Listing 6-12. Example step that uses the *core dump* command to check that execution paused in the *echo* function.

6.4.4 Managed Testing

Given a test written in the *Latch* test specification language, the framework will execute it through a single tester which manages one or more constrained testees. That is, the software under test runs on a constrained device and the test suite is kept on the unconstrained tester device. The tester will instruct the constrained device to perform tests by sending instructions step-by-step. This design allows test to be run on constrained devices, while overcoming the memory constraints.

In the example of Section 6.3 we configured a test suite in *Latch* to run on two devices. The test specification language has two main components to specify this configuration. First, the language has an overarching concept of a test suite that groups a number of tests. Each test suite runs independently of the others, and maintains its own devices, and their communication. Listing 6-13 shows the public methods of the *TestSuite* class in *Latch* that can add new devices and tests to a test suite. Finally, when a test suite is created and fully configured, it can be executed on all devices with the *run* method.

The devices passed to a test suite, represent a single connection to a device. *Latch* supports different devices each with their own abstraction, which needs to be able to connect and disconnect, upload a program, and send instructions. The interface of these abstractions is captured by the abstract class in Listing 6-14.

```
1 class TestSuite {  
2     public testee(name: string, testee: Testee): TestSuite;  
3     public scheduler(scheduler: Scheduler): TestSuite;  
4     public test(test: Test): TestSuite;  
5 }
```

Listing 6-13. The TestSuite allows developers to specify the testees, i.e., target devices, configure the scheduler, and the set of tests to be executed.

```
1 abstract class Testee {  
2     abstract connect(): Promise<void>;  
3     abstract upload(program: string): Promise<void>;  
4     abstract sendCommand<R>(command: Command<R>): Promise<R>;  
5     abstract disconnect(): Promise<void>;  
6 }
```

Listing 6-14. The Testee implements support for different devices to enable upload of programs, and command execution.

```
1 function celsius(fahrenheit: f32): f32 {  
2     return (fahrenheit - 32) * 0.556;  
3 }
```

Listing 6-15. AssemblyScript function to convert Fahrenheit to Celsius.

6.4.5 Using Test Scheduling and Expressing Dependent Tests

Performing tests on remote hardware testbeds is often slow, which delays feedback. To make testing on constrained devices part of continuous integration in practice, we reduce the time it takes to get feedback on failing tests by not running unnecessary ones. *Latch* allows dependencies between tests to be defined explicitly, as part of the test syntax as shown in Listing 6-5. Each test in *Latch* can specify a list of tests it depends on. The framework treats these dependencies between tests as transitive. This enables the framework to skip tests that cannot succeed, thereby mitigating the effects of the processing constraints.

6.4.5.1 Example

To illustrate test dependencies, we expand on our earlier multiplication test example. Suppose our constrained device is connected to a temperature sensor that uses Fahrenheit, but our software uses Celsius. For the conversion, we use the AssemblyScript function in Listing 6-15.

```
1 const dependentTest: Test = {
2   title: "Example Test with a dependency.",
3   program: "celsius.ts",
4   dependencies: [multiplicationTest],
5   steps: [{
6     title: "Fahrenheit to Celsius test",
7     instruction: invoke("celsius", [WASM.f32(46.4)]),
8     assert: returns(WASM.f32(-8.0))
9   }]
10};
```

Listing 6-16. *Latch* test suite for the `celsius` function, with a dependent scenario.

The conversion to Celsius depends on the multiplication of 32-bit floating point numbers, which we tested in our previous example. If the test for multiplication fails, we know that the `celsius` function will fail, too, and we can avoid running the temperature conversion test to save time. Consequently, we list the `multiplicationTest` as a dependency on Line 4 in Listing 6-16. Dependencies are entirely defined by the user, the only restriction is the disallowing of cyclical dependencies. Currently, the framework throws a runtime error whenever it encounters a cyclical dependency between a group of tests.

For complex scenarios, we can list an arbitrary number of *dependencies*. If any of the dependencies should fail, *Latch* skips the test. For continuous integration these tests are considered failing, but they are marked with a distinct *skipped* label and counted separately from true failures by *Latch*.

6.4.5.2 User-defined Schedulers

The order in which tests are executed can also influence the execution time of the test suite, especially since failing dependent tests can prevent unnecessary computations. To further speed up the execution, the test specification language allows developers to configure the scheduling algorithm the framework uses when running a test suite. The best scheduling algorithm depends on the exact test suites. Therefore, scheduling is configured at the level of a test suite as shown earlier in Listing 6-13. Scheduling algorithms are implemented as subclasses of the `Scheduler` class from the test specification language shown in Listing 6-17. The class only has one public method that takes a list of tests, and returns a new list with the tests sorted according to the scheduler's prioritization. This class allows developers to embed their own schedules in the test specification language.

The current implementation of the *Latch* framework, provides two predefined schedulers, the default and the optimistic scheduler. We give the

```

1 class Scheduler {
2     public schedule(tests: Test[]): Test[];
3 }
```

Listing 6-17. Schedulers enable custom ordering of tests. The ordering can avoid unnecessary test execution, or allow for test prioritization.

<pre> 1 Require list of tests suite 2 schedule ← [] 3 trees ← findDependencyGraphs(suite) 4 for tree <i>in</i> trees do 5 append schedule with breadth-first(tree) 6 end 7 return schedule</pre>	<pre> 1 Require list of tests suite 2 accumulator ← [][] 3 trees ← findDependencyGraphs(suite) 4 for tree <i>in</i> trees do 5 levels ← groupSiblings(tree) 6 for index, level <i>in</i> levels 7 append acc[index] with level 8 end 9 end 10 Return flatten(accumulator)</pre>
---	---

Algorithm 6-1. The default scheduling algorithm in *Latch*.

Algorithm 6-2. The optimistic scheduling algorithm to minimizing program uploads.

pseudocode for both scheduling algorithms in Algorithm 6-1 and Algorithm 6-2 respectively. Since dependencies amongst tests are transitive and cyclical dependencies are disallowed, we can extract trees from a test suite, where linked nodes depend on each other. Both algorithms will use this fact.

The default scheduler prioritizes the dependencies between tests and works best with test suites where a large number of tests dependent on a much smaller set of scenarios. The algorithm of the default scheduler, first finds all the dependency trees. The *findDependencyGraphs* function constructs a forest of directed dependence trees. In these graphs the nodes are tests that directly depend on their parents. The function will throw a runtime error if any cyclical dependencies are encountered. After the trees are found, the algorithm will append their tests breadth-first to the schedule. Within the same depth the tests are sorted alphabetically based on the program's name, to minimize the number of times the tester needs to upload code. The resulting list of tests, is ordered in such a way that trees are executed one after the other, and no test is ever run before any test it depends on.

The optimistic scheduler is built on the assumption that dependent tests are more likely to use the same program. If this is the case for the test suite, it can result in far fewer code uploads during a run compared to the default scheduler. The algorithm starts by initializing an accumulator as a list of

lists. Then, it constructs the dependence trees in the same way as the default scheduler. Next, for each tree the tests are aggregated into lists of tests with the same depth in the tree, the *siblings* in other words. Subsequently, the algorithm appends each group of siblings to the list in the accumulator that corresponds to its level. After all trees have been traversed, the accumulator is flattened to a one-dimensional list, and returned as the schedule.

The default scheduler iterates breadth-first over each dependence tree in succession. In contrast, the optimistic scheduler can be seen as traversing the entire dependence forest breadth-first. Again, at each depth the tests are sorted alphabetically according to their program. These two schedulers are provided as examples of scheduling algorithms, each test suite most likely has its own optimal algorithm.

Thanks to the scheduling based on the test dependencies, *Latch* can detect failures early and prevent unnecessary tests from running. However, the time needed for executing tests can be further minimized by executing test suites in parallel. Since microcontrollers are typically cheap and abundantly available, it makes sense to run different tests on separate devices at the same time. Currently, the schedulers still return a single ordering over the tests, but the dependency trees constructed as part of their algorithms offer an opportunity to parallelize. Different dependency trees can be safely run in parallel, since tests in different trees have no dependencies in common.

6.4.6 Handling and Reporting on Timeouts

Since all actions of a test are executed remotely, the tester cannot distinguish between an unresponsive test and a test that can still succeed after a long time. This is an unavoidable problem when testing in the presence of asynchronous actions. Many modern testing frameworks deal with this by adding timeouts to all asynchronous tests. In *Latch* we use timeouts for testing on constrained devices, too, but provide as much information as possible about where timeouts occur. Thus, *Latch* provides timeouts at the level of single instructions, following the example of frameworks dedicated to testing of asynchronous system (Haleby, n.d.), rather than merely at the level of a test, as is common practice in more general test frameworks (The JUnit Team, n.d., OpenJS Foundation, n.d., Python Software Foundation, n.d.). We found that debugging timeouts, is significantly easier with fine-grained information.

The actions of the tests are not the only source of asynchronicity in *Latch*. There are other asynchronous actions behind the scenes, from compiling test programs to connecting with hardware testbeds. In *Latch* every asynchronous action can time out, and each timeout has their own helpful message indented to make them easily identifiable by developers.

6.4.7 Detecting and Reporting Flaky Tests

The asynchronicity and non-determinism introduced by *Latch* and the hardware testbeds, can cause any test to become flaky. These tests can both succeed and fail for the same version of the software under test. In *Latch*, we follow the recommendation of Harman and O'Hearn (2018) to consider all tests as flaky. Indeed, flaky tests can hint at bugs. Therefore, we use an approach that improves the debuggability of flaky tests.

The framework can run in two modes. A normal mode which executes each action and each test at most once, and an analysis mode where tests are executed multiple times to analyze flakiness. In this mode we assume all tests are flaky. Therefore, tests are rerun even if they succeed. This can slow the test suite significantly, which is why it is provided as an optional mode. Indeed, the default mode still allows continuous integration to report initial results quickly, while the flakiness of the test suite can be reported at a later moment after the second mode has finished. The analysis mode trades performance for more information and certainty.

The analysis mode can be configured with a minimum and maximum number of runs. Since we consider all tests as flaky, we will execute each test at least the minimum number of times. If the test reports the same result for each of these runs, *Latch* assumes it is not flaky and stops for this scenario. In the other case, we already have proof that the test is flaky, and *Latch* will continue executing up to the maximum number of times to get a more representative measure of the flakiness. The maximum number of runs is important to have statistically significant results, and can therefore be configured by the user for each run. The minimum and maximum number of runs can be configured by the user. When a test suite is executed on multiple platforms, flakiness is measured for each platform separately. At the end of the analysis run, *Latch* reports the global flakiness of the test suite for each platform as the number of flaky scenarios, and at the end of the analysis run, *Latch* reports the flakiness on each platform for each test and gives an overview with the overall flakiness of the test suite for each platform separately and all platforms together.

6.4.8 Prototype Implementation

The prototype implementation of *Latch* is a TypeScript library built on the WARDUino (Lauwaerts et al., 2024) virtual machine for constrained devices and the Mocha testing framework for JavaScript and TypeScript.

WARDUino is a WebAssembly (Haas et al., 2017) virtual machine targeting ESP32 microcontrollers. The virtual machine also has basic debugging support, which we used as the basis for implementing our test instrumentation

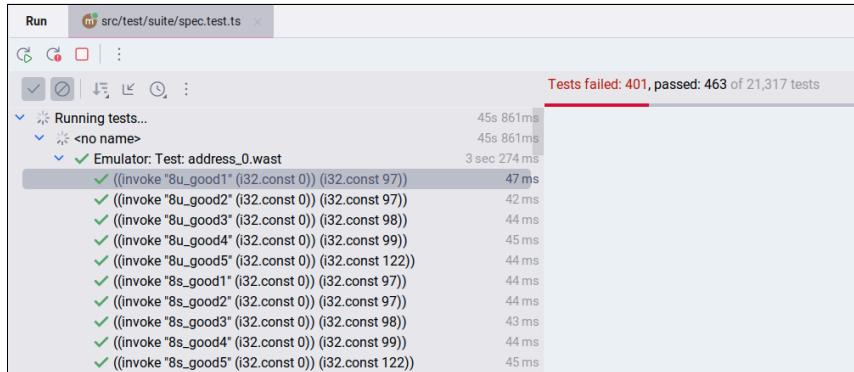


Figure 6-3. IDE integration in WebStorm (JetBrains s.r.o., 2023).

platform in *Latch*. By using a WebAssembly virtual machine, *Latch* can test programs written in any language that can compile to WebAssembly. This includes most of the mainstream programming languages used today, such as C, C++, Java, Python, Ruby, Rust (Fermion Technologies, Inc., 2023). In order to enable testing of a language fully, *Latch* needs to have support for compilation and sourcemapping. The current implementation has support for compiling and constructing sourcemaps for AssemblyScript.

We believe the general principles we use for implementing the *Latch* prototype on WARDuino, can be applied to any language or virtual machine which provides basic debugging support. This includes the C programming language that is supported by many microcontrollers, and which offers basic debugging by means of a JTAG interface.

The *Latch* prototype uses the Mocha testing framework for JavaScript and TypeScript to report the results of the tests in the *Latch* framework. Handling the output through an existing framework, immediately gives *Latch* integration into most of the existing IDEs used for programming in TypeScript and JavaScript.

6.5 Testing with *Latch*

Latch offers a framework for writing unconstrained automated test scripts, that can address many different testing scenarios. To demonstrate the versatility of *Latch*, we will present a common testing scenario for microcontrollers for each stage of the testing pyramid (Cohn, 2009). Several versions of the pyramid exist, often tailored to specific software domains (Mukhin et al., 2021). Generally, testing pyramids split testing into three or more stages, which are often performed in order from bottom to top. Each successive layer

in the pyramid tests larger parts of the software in one test. Therefore, each layer will typically have fewer tests than those before it. The testing pyramid is a common way of representing the full scope of testing for a software project, it is therefore suitable to showcase *Latch*'s ability to support the full range of testing scenarios.

In this section, we adhere to the classic testing pyramid, with unit testing at the bottom, followed by integration (or service) testing, and finally topped by end-to-end (user) testing. We first highlight how *Latch* can perform realistic, large-scale unit testing on constrained hardware. Then we show how *Latch* can test the instrumentation it uses as an illustration of integration testing. Finally, we show how manual testing on hardware can be automated to perform end-to-end testing. The example test suite illustrates how this can be used to test both the hardware itself, and the software libraries used for controlling that hardware.

6.5.1 Unit Testing: Large-scale Testing of a Virtual Machine

In the testing pyramid, the largest number of tests are the unit tests. The underlying virtual machine used by *Latch*, WARDuino, uses a subset of the official WebAssembly specification test suite, to test whether it conforms with the WebAssembly standard. WARDuino does not use the entire official test suite, since it does not yet support all the latest accepted proposals to the standard. The WARDuino project uses an extended version of the virtual machine to parse and run the unit tests from the test suite. Unfortunately, this means it cannot be executed on microcontrollers, since the entire suite needs to be included as well as the large parsing library needed to extract the unit tests. By using *Latch*, we are able to take the same test suite, and execute it on an ESP32 microcontroller. We discuss the results further in Section 6.6, in this section we focus on how the official specification test suite is written in *Latch*.

Test files in the WARDuino test suite contain a number of WebAssembly modules, each of which has a number of assertions. These assertions are so called *assert-return* tests, which invoke a WebAssembly function and specify the expected result. The assertions are written as S-expressions.⁶. Listing 6-18 shows two such assertions.

With *Latch*, we can run the same tests on actual embedded hardware. The structure of the WebAssembly specification test suite is well suited for *Latch*'s test specification language. The asserts coincide perfectly with the steps in the test. Each assert contains a single action to perform and a single assertion

⁶This conforms with the official WebAssembly specification tests, which can be found on: <https://github.com/WebAssembly/spec/tree/main/test/core>

```

1 (module (func (export "mul") (param $x f32) (param $y f32) (result f32) (f32.mul
  (local.get $x) (local.get $y))))
2 (assert_return (invoke "mul" (f32.const -0x0p+0) (f32.const 0x0p+0)) (f32.const
  -0x0p+0))
3 (assert_return (invoke "mul" (f32.const -0x1p-149) (f32.const -0x0p+0)) (f32.const
  0x0p+0))

```

Listing 6-18. An *assert-return* test from the official WebAssembly Specification test suite, testing the `f32.mul` operation.

```

1 const test: Test = { // Spec test
2   title: "Test f32.mul operation",
3   program: "module.wast",
4   steps: [
5     { title: "assert: -0 * +0 = -0",
6       instruction: Command.invoke("mul", args: [-0, 0]),
7       expect: returns(WASM.f32(-0)) },
8     { title: "assert: -1e-149 * -0 = 0",
9       instruction: Command.invoke("mul", [-1e-149, -0]),
10      expect: returns(WASM.f32(0)) }
11   ]
12 };

```

Listing 6-19. The `f32.mul` test has two steps, each checking the result of `mul` on different inputs.

to check. Therefore, all specification tests for WebAssembly can be encoded as a single test suite with a test for each distinct module. Listing 6-19 shows the example in Listing 6-18 translated into a *Latch* test.

To test the WARDuino virtual machine, we converted the official WebAssembly test specification into a large *Latch* test suite. Since *Latch* is a DSL embedded in TypeScript, this conversion can easily be done programmatically in TypeScript code. Converting the *assert-return* S-expressions to *Latch* syntax in this way is fairly, easy. The conversion enables us to test the WARDuino virtual machine incrementally. The test instrumentation framework will only load one WebAssembly module from the test suite at a time and each test is converted into steps, which are sent to the testee incrementally, i.e. the testing steps do not need to be stored in the memory of the testee. In Section 6.6, we give an overview of the performance of executing this test suite on an ESP32 device.

```
1 export function main(): void {
2     blink();
3     print("started blinking");
4 }
```

Listing 6-20. The blink program used by the integration test for the WARDuino debugger API.

```
1 const stepOverTest: Test = {
2     title: "Test STEP OVER",
3     program: "blink.wast",
4     dependencies: [dumpTest, invokeTest]
5     steps: [
6         { title: "Start program",
7             instruction: Command.invoke("main", [])
8         },
9         { title: "Send STEP OVER command",
10            instruction: Command.stepOver },
11         { title: "CHECK: execution stepped over direct call",
12            instruction: Command.dump,
13            expect: [{line: 3}]
14     ]
15 };
16 
```

Listing 6-21. The description for *Latch* of the **step over** test.

6.5.2 Integration Testing: Testing a Debugger API

Due to its design, *Latch* is well suited to test the debugging operations of the WARDuino virtual machine. Testing the debugger API exemplifies the second layer of the testing pyramid: integration testing.

As an example, consider the step over debug instruction, which steps over a single function call or a single instruction when the instruction does not call a function. A simple test starts at a function call and sends the debugging instruction, before checking if the program did step over it correctly.

The blink program in Listing 6-20 calls on Line 2 the `blink()` function and on Line 3 the `print()` function. With this program, we check that the program executes up to Line 3, rather than stopping at the start of the `main` function. Listing 6-21 shows the corresponding definition of a test in *Latch*. It loads the program, calls the `main` function, and sends a step over instruction. At the end of the test, it checks whether the current line has indeed moved to Line 3.

The debugging tests illustrate how integration tests can frequently depend on each other. For instance, our small *step over* test uses the `invoke` and `dump` instructions, which can also be tested with *Latch*. When tests for either these two instructions fail, we can no longer rely on the results of the *step over* test.

Since the *invoke* or *dump* commands may be broken, they might cause false positives, or false negatives, in tests that use them. There is no reason to run tests that cannot be trusted. In *Latch*, we can encode the dependency of the *step over* test on the *invoke* and *dump* command, by adding their tests to the list of dependent tests. With this information, *Latch* can prevent unnecessary or unreliable tests from slowing down the test suite, and delaying actionable feedback.

6.5.3 End-to-End Testing: Automating Manual Testing on Hardware

Developers of embedded software rely heavily on manual testing of their programs on the targeted hardware. The goal of manual testing is to verify that both the hardware and software of the system work correctly. It is equally important to check that the effects on the environment and the interaction between the hardware and the environment, work as intended. This kind of comprehensive end-to-end testing of embedded systems requires extensive control over the environment and conditions the hardware operates under, such as simulating user interactions, or controlling the input for sensors. These requirements account in large part for the ubiquity of manual testing, since they make automation of testing much more difficult.

Latch allows tests to control the behavior of the environment with local actions, and the behavior of the software under test through debugging instructions. This enables developers to script automated tests that correspond with manual testing scenarios.

When performing end-to-end testing on the hardware, whether manual or automated, things outside the control of the system can go wrong and cause the test to fail even though no part of the software under test is at fault. Such failures are often rare and non-deterministic, leading to flaky tests. The built-in detection and reporting of flaky tests in *Latch* is therefore important for end-to-end testing scenarios with the hardware.

6.5.3.1 Example: Testing MQTT Primitives

The WARDUINO virtual machine has a callback handling system that is used to implement different asynchronous IoT protocols (Lauwaerts et al., 2022), such as primitives for the MQTT protocol. Since the correct implementation of such protocols is crucial for applications, we need to test it extensively. Unfortunately, the public WARDUINO project currently has no automated tests for these components, especially since they require interaction with the device to be tested. The following example illustrates how *Latch* can be used to write end-to-end tests for both the callback system and the MQTT primitives. The example wants to verify the following two requirements:

```
1 function echo(topic: string, payload: string): void {
2     print(payload);
3 }
4
5 export function main(): void {
6     // ...
7     mqtt_init("broker.hivemq.com", 1883);
8     mqtt_subscribe("echo", echo);
9     // ...
10 }
```

Listing 6-22. Tiny MQTT program used to regression test the callback handling system in WARDuino.

1. After the subscribe primitive is called, the callback function should be registered for the correct topic in the virtual machine's callback system.
2. When an MQTT message is received the correct callback function should be called.

To test this functionality, we use a minimal program that subscribes on a single MQTT topic, and through a callback writes all messages it receives to the serial bus. An AssemblyScript implementation is shown in Listing 6-22.

The code in Listing 6-22, leaves out the code that connects to the Wi-Fi network, and checks the connection with the server whenever the program is idle. The example instead focuses on the three main things the program needs to do for the end-to-end test. It configures the MQTT server on Line 7, and subscribes to the *echo* topic on Line 8 with the callback function defined on Line 1. The scenario in Listing 6-23 uses the program to test the callback system and MQTT primitives of the WARDuino virtual machine on real hardware.

Many hardware-specific tests require the environment to behave in a controlled way. *Latch* makes no assumptions about the hardware and environment used for testing. Instead, the test specification language offers the ability to define local actions, through which the tester in the framework can manipulate and control the environment, both real and simulated.

The first step of the scenario invokes the main function, and the second step checks whether the echo callback was correctly registered in WARDuino's internal callback mapping. In the third step, the scenario sets a breakpoint at the callback function, so in the next step it can check if the callback is indeed called whenever an MQTT message is sent. To this end, the fourth step tells the tester to perform a local action. In the example, the *messageAndWait* function will send a message to the MQTT broker and wait until the testee reports that a breakpoint is hit. Once its promise resolves, we know a break-

```
1 const test: Test = { // MQTT test
2   title: "Test MQTT primitives",
3   program: "mqtt.ts",
4   dependencies: [testWiFi],
5   steps: [
6     { title: "Start program",
7       instruction: Command.invoke("main", []),
8     { title: "CHECK: callback function registered",
9       instruction: Command.dumpCallbackMapping,
10      expect: [
11        callbacks: (state, mapping) => mapping.some((map) => map["echo"].length >
12          0)}] },
13     { title: "Set breakpoint at *echo* callback",
14       instruction: Command.setBreakpoint(breakpointAtFunction("echo")) },
15     { title: "Send MQTT message and await breakpoint hit",
16       instruction: Actions.messageAndWait() },
17     { title: "CHECK: entered callback function",
18       instruction: Command.dump,
19       expect: [{mode: Mode.PAUSE}, {func: "echo"}] }
20   ];
21 };
22 
```

Listing 6-23. Test for the callback handling system in WARDuino, showing multiple steps and a custom assertion.

point is hit, and the final step double-checks whether we are indeed in the right function. When the promise is rejected, however, the action is marked as failing before continuing the scenario. This fifth step retrieves a dump of the current virtual machine state, and checks that WARDuino is paused and the current function corresponds to the *echo* callback function.

6.6 Performance Evaluation

The goal of *Latch* is to allow large-scale testing of IoT software on microcontrollers, and to enable users to write a versatile range of tests. The testing scenarios in the previous section illustrate the versatility of *Latch* to implement many testing strategies. Section 6.3 and Section 6.4 show how managed testing works, and what the *Latch* framework does to overcome the three challenges outlined in Section 6.2. In this section we provide empirical evidence to support our research question:

Question Is the managed testing approach, where tests are split into steps, sufficient for executing large-scale tests with *Latch*?

6.6.1 Test suites

To answer the question of performance, we execute a number of tests suites with *Latch* on an ESP32-WROVER IE and measure the runtime overhead compared to executing the same suites on a laptop. The test suites include the unit and debugging test suites presented in Section 6.5, and an additional test suite which is more computationally intensive. We chose these three types of test suites in order to have a wide range of tests that are unique in different aspects. The specification test suites from Section 6.5.1 are structurally identical, but test very different aspects of computer programs, ranging from memory manipulation, to control flow. The suites also represent a very common test pattern, unit testing through single function invocation, which is ubiquitous in many modern testing practices. The debugging test suite on the other hand, does not limit itself to just the invoke command, but uses the entire range of *Latch* commands in its tests, which also contain multiple steps. The computing test suite is structurally similar to the specification test suites, but is computationally more intensive, with steps that generally take at least an order of magnitude longer to perform.

Large Unit Test Suites. We use the WARDuino specification test suites as found in the public repository of the virtual machine, which we presented in Section 6.5.1. The collection contains 10,213 total tests across 25 test suites. The tests cover the operations on the numerical values, both integer and floating point, which are the only types of values in WebAssembly. The *copy*, *load*, *align*, and *address* categories test the WebAssembly memory, while the *local tee*, *local set*, *local get*, *nop*, *return*, *call indirect*, and *call* categories test stack manipulation. The remaining tests verify the structured control flow of WebAssembly. During the evaluation we used the default scheduling algorithm in *Latch*, and ran the test suites on a single remote testee.

The developers of the WARDuino virtual machine use simulation to test against the WebAssembly specification. However, the simulation ignores important hardware limitations. For instance, the memory of the simulated hardware is only limited by the amount of memory available to the host machine. Furthermore, to execute the specification tests, the WARDuino developers extended the simulator with a dedicated parsing library to parse the test suite written in S-expressions. This parsing library is too big to be run on the ESP32 and the S-expressions from the test suite alone, takes up 713 KB of memory. This is already more than twice the size of the microcontroller's memory, without including the WARDuino virtual machine, the parsing library, and the infrastructure to run the test suite. This means, that the WARDuino developers cannot currently test on the microcontrollers they target. However, when comparing the outcome of this approach with the output of the *Latch* version, we found no differences, giving us confidence

in the soundness of our framework. To assess the performance of *Latch*, we measure the overhead of executing the *Latch* test suites on a microcontroller compared with current practices, i.e. using a simulator.

WARDuino Debugger Test Suite. While the different specification test suites, test very different aspects, their structure are similar. We therefore include the debugger test suite outlined in Section 6.5, as an example that is not a traditional unit test suite. Rather than exclusively using the invoke command, this suite uses all commands available to *Latch*.

Computing Test Suite. As a final example, we include a test suite that unit tests a few simple mathematical operations, calculate the factorial, get the nth number in the fibonacci sequence, find the greatest common divider, and check if a number is prime. Similar to the specification test suites, the computing tests each include a single invoke step. However, while the steps in the other test suites are very fast, taking just a few milliseconds—the steps in this test suite can take several centiseconds.

6.6.2 Performance

All test suites are run separately on a Dell XPS 13 laptop using an 11th Gen Intel Core i7-1185G7 and 32 GB RAM memory, and the ESP32-WROVER IE microcontroller operating at a clock frequency of 240 MHz, and with 520 KiB SRAM, 4 MB SPI flash and 8 MB PSRAM. Each run starts by initializing the WARDuino instance, in the case of the microcontroller this entails flashing the entire virtual machine to the device. Whenever the test suites use different programs, they are uploaded with the *upload module* command, which allows *Latch* to update the program under test during a test suite, without needing to flash.

A detailed comparison of the overhead of executing the test suite is shown in Figure 6-4. The overhead on microcontroller is shown as relative to the simulator, and is the sample mean taken over 10 runs. *Latch* is run in its default mode without the flakiness analysis, where tests are run at most once. Each bar in this graph shows the overhead for executing one test suite on the hardware with *Latch*. The test suites are ordered from most steps, to least. The number of steps are shown next to each name, and the specification tests suites are highlighted in a different color.

All test suites shown in Figure 6-4 can be executed with *Latch* on the simulated version of WARDuino in approximately 10 minutes. Executing the same test suites directly on the ESP32, takes around 20 minutes. While the test suites take on average twice as long on the embedded device, the largest of the specification test suites run faster on the microcontroller. This is counterintuitive, but can be explained by the nature of the test suites.

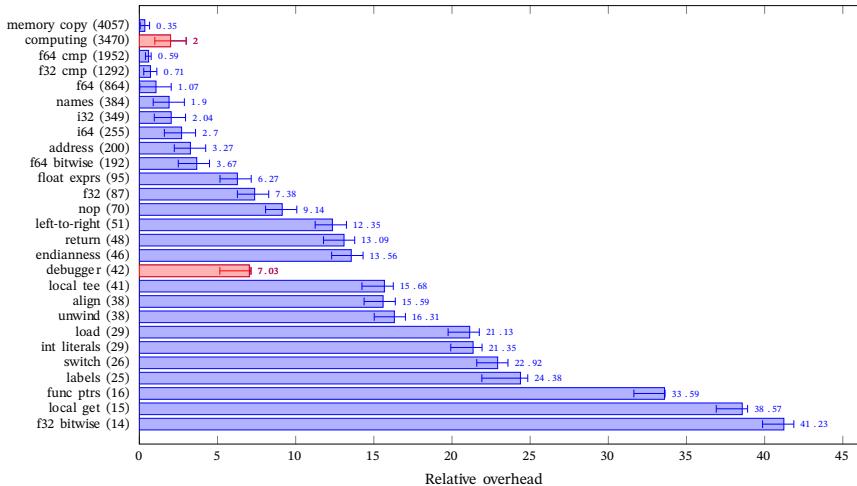


Figure 6-4. The relative runtime overhead of *Latch*'s WebAssembly specification test suite on hardware compared to a simulator for each test suite. Runtimes are calculated as sample means of 10 runs, and the exact relative overhead is shown next to each bar. The error bars show the confidence interval for the difference between the two means (normalized to the relative overhead) based on the Welch's t-test. The number of steps for each test suite is listed next to its name.

The steps in the specification test suites, are very simple tasks that are performed too quickly for any difference to be observed between the two devices. The overhead therefore becomes dominated by the communication, not the actual instructions themselves. The way the TypeScript framework handles the interprocess communication is evidently slower than the serial communication with the microcontroller over USB-C. However, the flashing at the start remains much slower than starting a new process on the laptop, therefore the overhead of the specification test suites with the fewest steps, is dominated by the startup phase instead. This results in the highest overhead overall.

The specification test suites taken separately in Figure 6-4, shows that fewer test steps results in higher overhead, because the execution time becomes dominated by the flashing process. This shows how important it is to prevent unnecessary flashing by using the *upload module* command. Conversely, more steps result in lower overhead, because the communication dominates the execution time of the steps. However, the debugger and computing test suites are major outliers, suggesting this is not the full story. For instance, the computing test suite contains 3,470 steps, but has a much higher overhead than the memory copy suite of a similar size. This is due to the steps in the

computing test suite being much more computationally intensive, and so much slower. Because the steps take longer to execute, the relative impact of the communication overhead is much lower. The debugger test suite on the other hand, has a much lower overhead than similarly sized specification test suites. This is because, invoke instructions used in the specification test suites, are quite slow compared to most of the other *Latch* commands, used in the debugger test suite. An entire user-defined function is run, in contrast to the step and dump command, which run a single instruction, or only send data. While the differences in structure among the test suites, reveals how many factors impact the performance of *Latch*, the results for the suites are roughly inline with each other. The results show that *Latch* performs well for our use-case of very large test suites of many small unit tests, which are very common in regression testing and continuous integration.

6.6.3 Summary

It is important for the validity of these results, that the test suites used here, are representative for the typical workloads of microcontroller software test suites. We consider this to be the case, since the specification, computing and debugger test suites are very different structurally, yet present very similar runtime performance. Additionally, we believe that the specification test suites are representative for microcontroller software testing. The suites use standard unit tests that invoke a function and check its results. It is no coincidence that these kinds of unit tests are so widely spread in test-driven development. They are an excellent way of testing that can be applied to almost any piece of software, regardless of its structure or programming paradigm. This also holds for microcontroller software. Moreover, the *invoke* instruction is one of the more expensive operations in *Latch*, since user defined functions may take very long to execute. Finally, the specification test suites are quite heterogeneous, since the categories test wildly different aspects of the virtual machine—from among others, control flow, arithmetic, stack manipulation, and memory access. For these reasons, we believe that this test suite is able to give a representative evaluation of *Latch*'s performance.

The performance results themselves, are impacted by an innumerable number of factors. Especially since the benchmarks are run on two devices, the framework on the laptop and the tests on the microcontroller. The communication between the two is an important factor in the runtime performance, and may be influenced by any number of factors, such as the operating system of either device, the configuration of the microcontroller, or the hardware (serial connection) itself. However, we believe given the size and number of repetitions, the performance figures are illustrative for the overall performance of managed testing with *Latch*.

In conclusion, we believe that our initial evaluation shows that the *Latch* framework and its managed testing approach present a realistic answer to our research question. The framework is able to automatically execute large-scale test suites on constrained devices with good performance, considering the limited processing power of the constrained devices. *Latch* performs the best for our most important use-case, test suites with high numbers of small unit tests for the same software under test. On the other hand, the performance overhead is highest when *Latch* needs to upload new software frequently. The *Latch* prototype has initial support for parallel execution on multiple constrained devices which can help mitigate this overhead, especially when many test programs can be uploaded simultaneously to different devices.

6.7 Related Work

Common software development practices such as regression testing, continuous integration, and test driven development, are much harder to adopt when working with microcontrollers. This is in large part due to the need to test on the physical hardware, specifically microcontrollers. There are very few solutions for single-target testing of software on microcontrollers. Ztest (Peress et al., 2024), Unity (PlatformIO, 2023a, VanderVoord et al., 2015), and ArduinoTest (Murdoch, 2023) are traditional unit testing frameworks for specific microcontroller architectures. Unfortunately, these frameworks do little to overcome the resource-constraints of microcontrollers themselves, and provide only the most standard unit testing functionality without any tailored solutions for testing on hardware. However, when testing on microcontrollers in this way, the test scenarios often rely on very specific hardware interactions as illustrated by our examples in Section 6.5. *Latch* addresses this lacuna with its novel testing methodology based on debugging methods. We are not aware of any testing framework that provides an alternative solution.

In this section, we will discuss the differences between *Latch* and the few exiting unit testing frameworks for microcontrollers further. In this chapter we have proposed a new way of testing on microcontrollers individually, but IoT systems are often tested as a whole in industry. While this kind of testing answers an entirely different set of demands than *Latch*, we do give a brief overview of these approaches here, for completeness. Similarly, testing plays a large role in general software development. As a result, a wide range of research topics are related to the *Latch* framework, of which not all have been previously applied to IoT. In the remainder of this section, we discuss *holistic IoT testing*, other *unit testing frameworks* broadly, *remote testing*, *scriptable debugging*, *test environments* for IoT programs, *device farms* for mobile applications, *conditional testing*, *test prioritization and selection*,

and *flaky tests*. Wherever possible, we include examples from IoT or microcontroller settings.

Unit Testing Frameworks

Constrained devices are still programmed primarily in low-level language such as C and C++. Many traditional unit testing frameworks are available for these languages, such as Google Test (GoogleTest, 2023), Boost.Test (Boost.Test team, 2023), CUTE (IFS Institut für Software, 2023), and bandit (Beyer and Karlsson, 2023). There are a handful of frameworks targeting microcontrollers explicitly, such as Unity (PlatformIO, 2023a, VanderVoord et al., 2015) and ArduinoTest (Murdoch, 2023). These work analogous to other unit testing frameworks, but are small enough to run on some constrained devices. While preferable over manual testing, these frameworks require the tests suites to be very small, since they are compiled and run along with the framework in their entirety on the device. In contrast, *Latch* allows arbitrarily large test suites.

Remote Testing

Latch's managed testing is adjacent to remote testing, but with some important differences. Remote testing is not a novel idea, for instance Jard et al. (1999) argued in 1999 that local synchronous tests can be translated to remote asynchronous tests without losing any testing power. Remote testing has mostly been used to test distributed systems (Yao and Wang, 2005).

The RobotFramework (Robot Framework Foundation, 2023) for instance, is a large testing framework that supports remote testing via an RPC interface offering a transparent distribution model. As argued in many papers “distribution transparency is a myth that is both misleading and dangerous” (Guerraoui, 1999, Lea, 1997, Waldo et al., 1997). The Latch framework takes into account these lessons and offers the test engineer a testing framework with inherit timeouts and support for flaky tests, going well beyond the RobotFramework.

Some examples of remote testing frameworks can also be found for constrained devices. The popular PlatformIO project (PlatformIO, 2023a), uses the Unity framework (VanderVoord et al., 2015) for remote testing. However, it works significantly different from how *Latch* executes large test suites. While *Latch* allows arbitrarily large test suites by executing tests step-by-step, Unity does not address the memory constraints of the target devices as it compiles and uploads test suites as one monolithic executable. The framework also does not provide the debugger-like scripts (with custom actions) supported by Latch that enable the automation of standard hardware tests.

Holistic IoT Testing

Existing tools for IoT testing focus largely on testing networked systems of many devices holistically (Kanstrén et al., 2018, Poperešnyak et al., 2018), rather than the more common approach where components are tested selectively. Holistic testing of networked systems are by and large incompatible with many of the common development practices; such as test driven development for instance, which relies on selective testing of single components. Moreover, wholesale testing of heterogeneous system is very difficult, so many testing tools instead focus on monitoring to try and detect errors (“AppOptics – APM and Infrastructure Tool | SolarWinds AppOptics,” n.d., Datadog, 2024). The few real testing frameworks available, tend to provide testing as a service (Kim et al., 2018). A recent research project developed an interesting framework for automatic testing of distributed *bluetooth mesh applications* with precise event scheduling, where tests are specified use a specific json format (Wieme et al., 2024). However, the work is focussed on a research setting, and benchmarking of new algorithms, rather than testing of software.

While holistic testing makes sense for IoT applications in industry, the approach makes far less sense for more consumer-oriented applications, such as smart home devices. Besides, developers cannot trust that end-to-end testing on such a high level, is enough to test IoT systems thoroughly. Neither does it lend itself well to test-driven development, as testing can only take place with a fully operational system. Therefore, there is a real need for selective—rather than holistic—testing of IoT software on microcontrollers. This is much easier with the single target testing in the style provided by *Latch*.

Scriptable Debugging

Latch's scriptable debugger-like hardware tests are inspired by scriptable debugging, which has been used in many other domains (Marceau et al., 2007). Scriptable debugging refers to all debugging techniques that can be controlled by developers through a programming language or similar tools such as regular expressions. Programmable debugging goes back to the early eighties, with many of the early proposals, such as Dispel (Johnson, 1981) and Dalek (Olsson et al., 1990), exploring variations on the concept of breakpoints. Recent work on a scriptable debugger API for Pharo (Dupriez et al., 2019), exposes a wide variety of advanced debugging operations, and allows developers to solve many challenging debugging scenarios through automated scripts. We are not aware of any framework which also applies the idea of scriptable debugging to testing in the context of constrained hardware.

Test Environments

A popular research topic in the domain of IoT testing, are heterogeneous test environments (Bures et al., 2020), where software can be distributed to nodes which are connected via a controlled network. This solution focuses on the challenging heterogeneity of IoT systems, and does not take into account the constraints the limited memory puts on the test suite size. Most test environments are virtual, and emulate the entire IoT environment (Nikolaïdis et al., 2021, Ramprasad et al., 2019, Symeonides et al., 2020).

While, simulators are widely used for testing Internet of Things systems (Bures et al., 2020), they can never capture all the aspects of real hardware (Khan et al., 2011, Roska, 1990). For example, bugs caused by mistakes in interrupt handling, incomplete or wrong configuration, and concurrency faults (Makhshari and Mesbah, 2021) are typically not simulated. Because accurate hardware emulation is difficult, modern simulators often incorporate parts of the hardware under test, as is the case for *hardware-in-the-loop simulations* (Mihalic et al., 2022). Similarly, some test environments do allow hardware to be integrated into their test environments, but still fundamentally rely on virtualization (Behnke et al., 2019, Keahay et al., 2020). There are far fewer works that look into full hardware test environments (Adjih et al., 2015, Burin Des Rosiers et al., 2012, Gluhak et al., 2011). Using these large test environments can give more control to the developer to change various aspects of the nodes and network, such as packet loss, latency, and so on. However, setting up such large and often complex systems is complicated and time-consuming, for that reason they are often provided as a service (Beilharz et al., 2022, Kim et al., 2018). Subsequently, the test environments confine users to the specific choices in hardware, virtualization, and network technologies made by the service. While these test environments reduce the overhead of setting up a testing lab, they do not fundamentally help developers overcome the hardware limitations faced when executing large test suites.

Device Farms

These test environments are sometimes called testing farms or device farms in case they use real hardware, and are a popular approach for testing mobile applications (Fazzini and Orso, 2020, Huang, 2014). Curiously, testing on devices seems much more prevalent in the field of testing mobile applications (Kong et al., 2019). We believe this might be because mobile devices have far more memory than the embedded devices targeted by *Latch*, and therefore have no problem running large test suites. This strengthens our view that testing on constrained hardware presents a worthwhile research direction. However, the existing device farms heavily target mobile devices, and again limit users to the chosen technologies and hardware.

Conditional testing

Dependencies in *Latch* can be viewed as conditional skips for tests, where a test is skipped if any of the scenarios it depends on fail. Conditional skips have been around for some time in unit testing frameworks, such as the pytest framework for the Python language (Krekel and team, 2023), and the JUnit framework for Java (Bechtold et al., 2023). Pytest includes a *skipif* annotation which takes a boolean expression as its argument. In JUnit developers can use the *Assume* class, which provides a set of methods for conditional execution of tests. Modern frameworks targeting constrained devices (Murdoch, 2023, PlatformIO, 2023b) do not support conditional tests.

Test prioritization and selection

Another purpose of the dependencies in the test description language, are to determine the order tests are run in. Research on software testing has recently increased its attention to test prioritization and test selection (Pan et al., 2021). These techniques can also be applied to testing IoT systems (Medhat et al., 2020), where they are particularly useful since they can reduce large test suites to the most important tests, and help prioritize tests in such a way that regression tests fail as early as possible. An interesting line of future research could focus on integrating these techniques in *Latch*.

Flaky Tests

Flaky tests represent an active domain of research (Parry et al., 2021), which focuses on three problems: detecting flaky tests, finding root causes, and fixing flaky tests (Zolfaghari et al., 2021). The first step is to detect which tests are flaky. A popular approach is to look at the code coverage of tests (Bell et al., 2018, Zolfaghari et al., 2021). Once a flaky test is found, the next step is to find the root cause of the flaky test. This is a considerably harder problem, which is still being actively worked on (Lam et al., 2019). Alternatively, some research looks into automatically fixing, or preventing, flaky tests (Shi et al., 2019). All these techniques, from detection to fixing, are developed with the ultimate goal of mitigating and preventing flaky tests. In contrast, *Latch* focuses on providing a simple way of detecting and measuring the number of flaky tests in a test suite run. When evaluating *Latch*, we encountered flaky tests only rarely, but we believe that further research is warranted to assess the degree in which testing on constrained devices can cause flaky tests, and how existing techniques can mitigate them.

6.8 Conclusion

Testing is an essential part of the software development cycle which is currently very challenging on constrained devices. The limited memory and processing power of these constrained devices restrict the size of the test suite and makes testing slow, impeding a fast feedback loop. Moreover, due to the non-deterministic and unpredictable environment, tests can become flaky.

In this chapter, we answered the question of how to design and implement a testing framework for automatically running large-scale versatile tests on constrained systems. We introduce our novel testing framework *Latch* (Large-scale Automated Testing on Constrained Hardware), which needed to overcome three challenges; the memory constraints, processing constraints, and the timeouts and flaky tests. In essence, *Latch* splits test suites into small test instructions which are sent by a managing tester to a managed testee (constrained device). Because the constrained device receives the test instructions incrementally from the tester, it does not need to maintain the whole test suite in memory. By using an unconstrained tester to manage the constrained devices and the test suites, *Latch* is able to overcome the memory constraints.

Our testing framework further allows programmers to indicate the dependencies between related tests. This dependency information is used by *Latch* to skip tests that depend on previously failing tests, thus resulting in a faster feedback loop and helping the framework overcome the processing constraints of microcontrollers. On top of that *Latch* addresses the issue of timeouts and flaky tests, by including an analysis mode that provides feedback on timeouts and the flakiness of tests. Finally, the framework uses a novel approach of debugging-like instructions to allows developers to automate manual testing on hardware.

To demonstrate the efficacy and versatility of *Latch*, we showcased three use-cases, each pertaining to one stratum of the testing pyramid. The first use-case exemplifies unit testing, and showcases how we implemented a large suite of unit tests in *Latch* for a WebAssembly virtual machine intended for constrained devices. This test suite consists of 10,213 unit tests for a virtual machine running on a small ESP32 microcontroller. The second use-case illustrates integration testing of the instrumentation API in *Latch*. The third use-case highlights how the *Latch* test specification language allows programmers to write debugging-like testing scripts to test more elaborate testing scenarios, that mimic common manual testing tasks. Benchmarks show that the overhead of the testing framework is within expectation, roughly matching the performance difference between the constrained hardware and using a simulator on a workstation. Our test-cases shows that

the testing framework is expressive, reliable, and reasonably fast, making it suitable to run large test suites on constrained devices.

Chapter 7

Conclusion

Why do you go away? So that you can come back. So that you can see the place you came from with new eyes and extra colors. And the people there see you differently, too. Coming back to where you started is not the same as never leaving.

— Terry Pratchet, *A Hat Full of Sky*

This dissertation introduced three new ways of debugging embedded systems, based on a virtual machine approach with sound, and complete debugging semantics. However, the dissertation had a wider purpose, to examine how to design debuggers well, and how to apply these techniques under tight constraints. While we have discussed the conclusions for each of the contributions in their respective chapters, we now consider the bigger picture one last time and look back at the journey taken in this dissertation.

7.1 Reflections on Debugging in Constrained Environments

The research in this dissertation touched on many different challenges of debugging and development on constrained devices. The work was built on top of the WARDUINO virtual machine. WARDUINO served both as the general instrumentation platform on which debuggers could be built, and as a more modern development environment to improve the programming experience of developers. In this way the virtual machine simultaneously addresses both challenges C2 and C3 introduced in Chapter 1.

- C2** Current embedded software development uses low-level compiled programming languages and bare-metal execution environments that make it difficult to instrument the software running on the constrained devices.
- C3** Current embedded software development is characterized by a cumbersome development experience due to low-level coding, lack of portability across platforms, slow deployment, hardware limitations, and limited debugger options.

WARDuino as a WebAssembly virtual machine is able to provide developers with a series of new tools that can speed up the development process significantly. Primarily, the remote debugger built on top of the WARDuino virtual machine eliminates the need to use laborious hardware debuggers, and provides partial over-the-air code updates to reduce the need for reflashing the entire software. By using WebAssembly as the target language, developers can choose from a wide range of high-level languages to write their embedded software. Additionally, we can leverage the existing tooling and ecosystem around WebAssembly to provide, for instance, easier ways to write emulators using existing web technology. Finally, the portability of WebAssembly makes it much easier to support different platforms—making WARDuino programs much more portable than existing embedded software.

However, the remote debugger is limited by the same resource constraints as the embedded software. This led us to challenge C4.

C4 The *memory limitations* of embedded devices make it difficult to run debuggers alongside the target software, and the *processing constraints* prevent the adoption of more advanced debugging techniques.

In order to overcome the hardware limitations of embedded devices, we found that it is possible to largely evade the constraints by moving the debugging session from the constrained device (*server*) to a more powerful host machine (*client*). This corresponds to the out-of-place debugging approach, first developed for big data applications to reduce debugging interference.

We adapted out-of-place debugging to work on the embedded devices, and presented a novel out-of-place debugger for WebAssembly programs running on embedded devices. Any non-transferable resources of the original constrained device, such as sensors and actuators, can still be accessed during the debugging session, to provide the illusion of remote debugging. Such non-transferable resources can have both stateless and stateful natures, and access to them can be both synchronous and asynchronous. In our novel out-of-place solution, we are the first to address all of these aspects—leading to what we call *stateful out-of-place debugging*.

C5 Typical *interrupt-driven programs* interfere with live debugging processes by arbitrarily changing the execution flow of a program.

Embedded software is generally written in an *interrupt-driven* style, which means that execution flow during online debugging can be arbitrarily interrupted and diverted. This makes it very difficult to debug such programs.

Our stateful out-of-place debugger, captures all asynchronous events on the remote constrained device, and forwards them to the local *client* debugger without triggering them. This means that debugging sessions are no longer

arbitrarily interrupted by asynchronous events, but our stateful out-of-place debugger is not just able to capture and forward asynchronous resources. The debugger also provides developers with some control over the asynchronicity. On the *client* side, developers can choose when to trigger the asynchronous events, allowing them some control over their order and timing within the program.

Yet, the out-of-place debugger only touched the surface the challenges in debugging embedded interrupt-driven programs. The larger problem is how to deal with non-deterministic behavior of input and output in general.

C6 Current embedded debuggers are not equipped to *debug non-deterministic bugs* caused by their I/O intensive nature.

In Chapter 5, we presented the first multiverse debugger designed for microcontrollers, called *MIO*, addressing the challenge of non-deterministic bugs caused by unpredictable I/O. Unlike prior approaches limited to abstract settings, our debugger integrates with a full WebAssembly virtual machine and supports a range of concrete I/O primitives—including sensors, pins, and motors—while maintaining formal soundness.

By introducing a sparse snapshotting strategy, we achieve practical performance on resource-constrained devices. This work demonstrates that multiverse debugging can work as an online debugger, and be made viable for real-world embedded systems.

7.2 Reflections on the General Implications

The works in this dissertation provide more general contributions not limited to embedded systems.

Our formalization of stateful out-of-place debugging, is the first formalization of the technique, and is not limited to embedded systems. The state synchronisation problem is a general issue for out-of-place debugging, and our solution is likewise ; we hope in future work to formalize the approach in a more fundamental way, by using a more general underlying language model, such as CEK machines (Felleisen and Friedman, 1986). However, our formalization is already quite general, and includes very little WebAssembly specific aspects.

Similarly our solution to challenge C6 applies to online multiverse debugging in general.

C7 How can multiverse debugging be applied to concrete executions and enable live exploration of the multiverse in the presence of I/O?

Our online multiverse debugger allows developers to freely navigate the multiverse of possible execution paths, without the need for a full program replay. Interactions with the external environment are automatically reversed and replayed as needed by the debugger, enabling developers to explore the impact of I/O operations on program behavior without worrying about interference from the debugger.

Of course, since we work with a real-world environment, we cannot guarantee that the debugger will be able to reverse all I/O operations correctly. However, we can guarantee that the debugger will reverse the I/O actions supported by the virtual machine. These I/O actions are designed to be *deterministically compensable* by the virtual machine, meaning that the virtual machine can always reverse them.

Our formal model of the *MIO* debugger allows us to clearly show exactly how actions are reversed, and to proof that our debugger is still sound even when reversing action, or sliding to new universes. While the spare snapshotting is designed to make the technique work on constrained systems, the approach described by our formal semantics can be applied to any setting.

7.3 Applying the Lessons Learned to Testing

Our novel testing framework *Latch* uses a similar principle as out-of-place debugging to run large suites of tests on the constrained hardware itself. Coupled with our novel managed testing approach, which allows developers to integration test their embedded software through more realistic scenarios, we are able to provide a considerably better way of testing embedded software.

7.4 Soundness and completeness of debuggers

The debuggers that are the subject of this dissertation are all manual online debuggers, for which we define soundness as the property that the debugger observes all possible behavior of the program being debugged, and does not deviate from it.

Like many conventional debuggers, our remote debugger—while complete—is not sound, since it can update the code of the program being debugged during the debugging session. However, without the live code updates, we were able to prove soundness for the remote debugging. Through significant efforts we were likewise able to design an entirely new class of out-of-place and multiverse debuggers, which are both sound and complete. This

gives developers greater confidence in the reliability of their observations, especially when debugging non-deterministic bugs.

The formal soundness of our debuggers is necessarily limited to certain assumptions, since we can never fully eliminate the probe effect of online debuggers, or discount the possible noise of the real-world environment in which embedded devices operate. In the case of our multiverse debugger, we assume in the formalization that I/O operations do not influence each other. In the implementation we have some early support for defining predictable dependencies between I/O operations, but this is not yet formalized. An interesting future direction would be to extend our formalization to capture more of the possible dependencies between I/O operations, and to provide a formal soundness proof for this extended model.

Similarly for the stateful out-of-place debugger, we assume that there is a known partial order of the possible asynchronous events of a program. This is a reasonable assumption for many programs, but does present a very naive model. Extending this model to capture more of the possible dependencies between asynchronous events, perhaps even to capture certain timing aspects, is a very useful future direction. There is quite some work on causal consistency and environment modeling which could help us here.

Finally, while we believe *completeness* and *soundness* encompass the most fundamental expectation of debugger operations—that they do not interfere with the program’s execution—there are many other aspects of debuggers that are important to consider. In future work, we hope that different aspects can be examined and formalized in a similar way.

7.5 Reflections on the Future

Reflecting further on the lessons learned, we see four large lessons that can lead to new avenues of research.

First, by adopting out-of-place debugging and solving the state synchronisation problem we are now able to apply more complex debugging techniques to constrained devices. While we have given some indication in this dissertation, we have only scratched the surface of this advantage. One area where we see great potential is that of live programming. The stateful out-of-place debugger provides a perfect platform on top of which to build a live programming environment. The offloading of most of the execution to the local device where the developer is actually programming, allows for easier integration of custom visualisations and other live programming tools without the constraints of the embedded devices.

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Chapter 7. Conclusion

Second, the multiverse debugger our work has hopefully shown that multiverse debugging can work extremely well as a live online debugging approach—we would even argue that it works best in this scenario. However, we learned that this adds several new dimensions and challenges to the technique.

In the first place we now need to handle the output effects of the program, which remains a difficult problem to solve in new settings. The formal framework with sparse snapshotting we developed in this thesis can pave the way here. Yet other challenges remain, such as the state explosion. In the context of online multiverse debugging this problem gets a new dimension, as branches are discovered by piecemeal exploration during the debugging session. It is easy for new branches introduced in this way to be identical to previous branches and therefore redundant. This is a clear problem that needs to be solved to unlock the real potential of online multiverse debugging. In fact, we have already made a first step in this direction using concolic execution to prune redundant paths. This integration has several additional advantages as it can also help guide developers in their exploration.

This research
is being led by
Maarten
Steevens at
UGent.

Third, the soundness and completeness distill the lessons we learned around the correctness and formalisation of debuggers in two clear theorems. We have discussed the implications and limitations of these theorems already at length as they present perhaps the most important lessons of this dissertation. They also present an unfinished ambition, and we hope that in future research the community can find a consensus on the correctness of debuggers.

Fourth, the managed testing approach developed to test our debuggers presents a interesting and unique combination of debugging and testing. Quite accidentally we learned that it is possible to build an automatic integration testing framework on top of debuggers, and that this gives developers a wide range of tools. This lies at the basis of the managed testing approach. The debugger controls the software and performs scenarios throughout which the testing framework can verify predefined assertions. It seems clear to us that this is a more widely applicable approach, and we hope to see more testing frameworks and research integrate tools from the debugging world.

Bibliography

- Adjih, C., Baccelli, E., Fleury, E., Harter, G., Mitton, N., Noel, T., Pissard-Gibollet, R., Saint-Marcel, F., Schreiner, G., Vandaele, J., Watteyne, T., 2015. FIT IoT-LAB: A Large Scale Open Experimental IoT Testbed, in: IEEE World Forum on Internet of Things, WF-IoT 2015 - Proceedings. pp. 459–464.. <https://doi.org/10.1109/WF-IoT.2015.7389098>
- Agrawal, H., De Millo, R., Spafford, E., 1991. An Execution-Backtracking Approach to Debugging. *IEEE Software* 8, 21–26.. <https://doi.org/10.1109/52.88940>
- Almeida, P.S., 2024. Approaches to Conflict-free Replicated Data Types. *ACM Comput. Surv.* 57, 1–36.. <https://doi.org/10.1145/3695249>
- Alter the Program's Execution Flow, 2024.
- Annamaa, A., 2015. Introducing Thonny, a Python IDE for Learning Programming, in: Proceedings of the 15th Koli Calling Conference on Computing Education Research, Koli Calling '15. Association for Computing Machinery, New York, NY, USA, pp. 117–121.. <https://doi.org/10.1145/2828959.2828969>
- AppOptics – APM and Infrastructure Tool | SolarWinds AppOptics, n.d.
- Aspencore, 2023. Embedded Survey 2023: More IP Reuse as Workloads Surge.
- The AssemblyScript Project, 2023. AssemblyScript.
- Auguston, M., Michael, J.B., Shing, M.-T., 2005. Environment Behavior Models for Scenario Generation and Testing Automation. *SIGSOFT Softw. Eng. Notes* 30, 1–6.. <https://doi.org/10.1145/1082983.1083284>
- Axelsen, H.B., Glück, R., 2016. On Reversible Turing Machines and Their Function Universality. *Acta Informatica* 53, 509–543.. <https://doi.org/10.1007/s00236-015-0253-y>
- Aycock, J., 2003. A Brief History of Just-in-Time. *ACM Comput. Surv.* 35, 97–113.. <https://doi.org/10.1145/857076.857077>
- Baccelli, E., Doerr, J., Jallouli, O., Kikuchi, S., Morgenstern, A., Padilla, F.A., Schleiser, K., Thomas, I., 2018. Reprogramming Low-end IoT Devices from the Cloud, in: 2018 3rd Cloudification of the Internet of Things (CIoT). pp. 1–6.. <https://doi.org/10.1109/CIOT.2018.8627129>
- Backus, J.W., Beeber, R.J., Best, S., Goldberg, R., Haibt, L.M., Herrick, H.L., Nelson, R.A., Sayre, D., Sheridan, P.B., Stern, H., Ziller, I., Hughes, R.A.,

Bibliography

- Nutt, R., 1957. The FORTRAN Automatic Coding System, in: Papers Presented at the February 26-28, 1957, Western Joint Computer Conference: Techniques for Reliability, IRE-AIEE-ACM '57 (Western). Association for Computing Machinery, New York, NY, USA, pp. 188–198.. <https://doi.org/10.1145/1455567.1455599>
- Bahlke, R., Snelting, G., 1986. The PSG System: From Formal Language Definitions to Interactive Programming Environments. ACM Trans. Program. Lang. Syst. 8, 547–576.. <https://doi.org/10.1145/6465.20890>
- Baldoni, R., Coppa, E., D'elia, D.C., Demetrescu, C., Finocchi, I., 2018. A Survey of Symbolic Execution Techniques. ACM Comput. Surv. 51, 1–39.. <https://doi.org/10.1145/3182657>
- Balzer, R.M., 1969. EXDAMS: Extendable Debugging and Monitoring System, in: Proceedings of the May 14-16, 1969, Spring Joint Computer Conference, AFIPS '69 (Spring). Association for Computing Machinery, New York, NY, USA, pp. 567–580.. <https://doi.org/10.1145/1476793.1476881>
- Banken, H., Meijer, E., Gousios, G., 2018. Debugging Data Flows in Reactive Programs, in: Proceedings of the 40th International Conference on Software Engineering, ICSE '18. Association for Computing Machinery, New York, NY, USA, pp. 752–763.. <https://doi.org/10.1145/3180155.3180156>
- Banks, A., Gupta, R., 2014. MQTT Version 3.1. 1. OASIS standard 29.
- Banzi, M., 2008. Getting Started with Arduino, 99th ed. Make Books - Imprint of: O'Reilly Media, Sebastopol, CA.
- Battagline, R., 2021. The Art of WebAssembly: Build Secure, Portable, High-Performance Applications. No Starch Press.
- Bechtold, S., Brannen, S., Link, J., Merdes, M., Philipp, M., de Rancourt, J., Stein, C., 2023. JUnit 5 User Guide.
- Behnke, I., Thamsen, L., Kao, O., 2019. Héctor: A Framework for Testing IoT Applications Across Heterogeneous Edge and Cloud Testbeds, in: Proceedings of the 12th IEEE/ACM International Conference on Utility and Cloud Computing Companion, UCC '19 Companion. Association for Computing Machinery, New York, NY, USA, pp. 15–20.. <https://doi.org/10.1145/3368235.3368832>
- Beilharz, J., Wiesner, P., Boockmeyer, A., Pirl, L., Friedenberger, D., Brokhausen, F., Behnke, I., Polze, A., Thamsen, L., 2022. Continuously Testing Distributed IoT Systems: An Overview of~the~State of~the~Art, in: Hadid, H., Aldwairi, M., Bouadjenek, M.R., Petrocchi, M., Faci, N., Outay, F., Beheshti, A., Thamsen, L., Dong, H. (Eds.), Service-Oriented

- Computing – ICSOC 2021 Workshops. Springer International Publishing, Cham, pp. 336–350.. https://doi.org/10.1007/978-3-031-14135-5_30
- Bell, J., Legunsen, O., Hilton, M., Eloussi, L., Yung, T., Marinov, D., 2018. DeFlaker: Automatically Detecting Flaky Tests, in: 2018 IEEE/ACM 40th International Conference on Software Engineering (ICSE). pp. 433–444.. <https://doi.org/10.1145/3180155.3180164>
- Beller, M., Spruit, N., Spinellis, D., Zaidman, A., 2018. On the Dichotomy of Debugging Behavior among Programmers, in: Proceedings of the 40th International Conference on Software Engineering, ICSE '18. Association for Computing Machinery, New York, NY, USA, pp. 572–583.. <https://doi.org/10.1145/3180155.3180175>
- Bennett, C.H., 1988. Notes on the History of Reversible Computation. IBM Journal of Research and Development 32, 16–23.. <https://doi.org/10.1147/rd.321.0016>
- Bernardo, M., Lanese, I., Marin, A., Mezzina, C.A., Rossi, S., Sacerdoti Coen, C., 2023. Causal Reversibility Implies Time Reversibility, in: Jansen, N., Tribastone, M. (Eds.), Quantitative Evaluation of Systems. Springer Nature Switzerland, Cham, pp. 270–287.. https://doi.org/10.1007/978-3-031-43835-6_19
- Bernstein, K.L., Stark, E.W., 1995. Operational Semantics of a Focusing Debugger. Electronic Notes in Theoretical Computer Science, MFPS XI, Mathematical Foundations of Programming Semantics, Eleventh Annual Conference 1, 13–31.. [https://doi.org/10.1016/S1571-0661\(04\)80002-1](https://doi.org/10.1016/S1571-0661(04)80002-1)
- Beyer, S., Karlsson, J., 2023. Bandit. Human-friendly Unit Testing for C++11.
- Blackburn, M., 1998. Using Models for Test Generation and Analysis, in: 17th DASC. AIAA/IEEE/SAE. Digital Avionics Systems Conference. Proceedings (Cat. No.98CH36267). p. C45/1–C45/8 vol.1.. <https://doi.org/10.1109/DASC.1998.741501>
- Bojanova, I., Eduardo Galhardo, C., 2021. Classifying Memory Bugs Using Bugs Framework Approach, in: 2021 IEEE 45th Annual Computers, Software, And Applications Conference (COMPSAC). pp. 1157–1164.. <https://doi.org/10.1109/COMPSAC51774.2021.00159>
- Boost.Test team, 2023. What Is Boost.Test?.
- Boothe, B., 2000. Efficient Algorithms for Bidirectional Debugging, in: Proceedings of the ACM SIGPLAN 2000 Conference on Programming Language Design and Implementation, PLDI '00. Association for Com-

Bibliography

- puting Machinery, New York, NY, USA, pp. 299–310.. <https://doi.org/10.1145/349299.349339>
- Brus, T.H., van Eekelen, M.C.J.D., van Leer, M.O., Plasmeijer, M.J., 1987. Clean — A Language for Functional Graph Rewriting, in: Kahn, G. (Ed.), Functional Programming Languages and Computer Architecture, Lecture Notes in Computer Science. Springer, Berlin, Heidelberg, pp. 364–384.. https://doi.org/10.1007/3-540-18317-5_20
- Bures, M., Klima, M., Rechtberger, V., Bellekens, X., Tachtatzis, C., Atkinson, R., Ahmed, B.S., 2020. Interoperability and Integration Testing Methods for IoT Systems: A Systematic Mapping Study, in: de Boer, F., Cerone, A. (Eds.), Software Engineering and Formal Methods. Springer International Publishing, Cham, pp. 93–112.
- Burg, B., Bailey, R., Ko, A.J., Ernst, M.D., 2013. Interactive Record/Replay for Web Application Debugging, in: Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology, UIST '13. Association for Computing Machinery, New York, NY, USA, pp. 473–484.. <https://doi.org/10.1145/2501988.2502050>
- Burin Des Rosiers, C., Chelius, G., Fleury, E., Fraboulet, A., Gallais, A., Mitton, N., Noël, T., 2012. SensLAB: Very Large Scale Open Wireless Sensor Network Testbed. Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering 239–254.. https://doi.org/10.1007/978-3-642-29273-6_19
- Burow, N., Carr, S.A., Nash, J., Larsen, P., Franz, M., Brunthaler, S., Payer, M., 2017. Control-Flow Integrity: Precision, Security, and Performance. ACM Comput. Surv. 50, 1–33.. <https://doi.org/10.1145/3054924>
- Cadar, C., Godefroid, P., Khurshid, S., Pašareanu, C.S., Sen, K., Tillmann, N., Visser, W., 2011. Symbolic Execution for Software Testing in Practice: Preliminary Assessment, in: Proceedings of the 33rd International Conference on Software Engineering, ICSE '11. Association for Computing Machinery, New York, NY, USA, pp. 1066–1071.. <https://doi.org/10.1145/1985793.1985995>
- Calikli, G., Bener, A., Arslan, B., 2010. An Analysis of the Effects of Company Culture, Education and Experience on Confirmation Bias Levels of Software Developers and Testers, in: Proceedings of the 32nd ACM/IEEE International Conference on Software Engineering - Volume 2, ICSE '10. Association for Computing Machinery, New York, NY, USA, pp. 187–190.. <https://doi.org/10.1145/1810295.1810326>
- Catolino, G., Palomba, F., Zaidman, A., Ferrucci, F., 2019. Not All Bugs Are the Same: Understanding, Characterizing, and Classifying Bug Types.

- Journal of Systems and Software 152, 165–181.. <https://doi.org/10.1016/j.jss.2019.03.002>
- Chattpadhyay, S., Nelson, N., Au, A., Morales, N., Sanchez, C., Pandita, R., Sarma, A., 2022. Cognitive Biases in Software Development. *Commun. ACM* 65, 115–122.. <https://doi.org/10.1145/3517217>
- Chen, S.-K., Fuchs, W., Chung, J.-Y., 2001. Reversible Debugging Using Program Instrumentation. *IEEE Transactions on Software Engineering* 27, 715–727.. <https://doi.org/10.1109/32.940726>
- Church, A., 1940. A Formulation of the Simple Theory of Types. *Journal of Symbolic Logic* 5, 56–68.. <https://doi.org/10.2307/2266170>
- Clang contributors, 2021. Clang: A C Language Family Frontend for LLVM.
- Cohen, I., 1994. The Use of "Bug" in Computing. *IEEE Annals of the History of Computing* 16, 54–55.. <https://doi.org/10.1109/85.279235>
- Cohn, M., 2009. Succeeding with Agile: Software Development Using Scrum, 1th. ed. Addison-Wesley Professional, Boston, MA, USA.
- D'Silva, V., Kroening, D., Weissenbacher, G., 2008. A Survey of Automated Techniques for Formal Software Verification. *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems* 27, 1165–1178.. <https://doi.org/10.1109/TCAD.2008.923410>
- da Silva, F.Q.B., 1992. Correctness Proofs of Compilers and Debuggers : An Approach Based on Structural Operational Semantics.
- Dalal, S.R., Jain, A., Karunanithi, N., Leaton, J.M., Lott, C.M., Patton, G.C., Horowitz, B.M., 1999. Model-Based Testing in Practice, in: Proceedings of the 21st International Conference on Software Engineering, ICSE '99. Association for Computing Machinery, New York, NY, USA, pp. 285–294.. <https://doi.org/10.1145/302405.302640>
- Danos, V., Krivine, J., 2004. Reversible Communicating Systems, in: Gardner, P., Yoshida, N. (Eds.), CONCUR 2004 - Concurrency Theory. Springer, Berlin, Heidelberg, pp. 292–307.. https://doi.org/10.1007/978-3-540-28644-8_19
- Datadog, 2024. End to End Testing Automation.
- De Sio, C., Azimi, S., Sterpone, L., 2023. Evaluating Reliability against SEE of Embedded Systems: A Comparison of RTOS and Bare-Metal Approaches. *Microelectronics Reliability* 115124.. <https://doi.org/10.1016/j.microrel.2023.115124>

Bibliography

- de Troyer, C., Nicolay, J., de Meuter, W., 2018. Building IoT Systems Using Distributed First-Class Reactive Programming, in: 2018 IEEE International Conference on Cloud Computing Technology and Science (CloudCom). pp. 185–192.. <https://doi.org/10.1109/CloudCom2018.2018.00045>
- Deiner, A., Fraser, G., 2024. NuzzleBug: Debugging Block-Based Programs in Scratch, in: Proceedings of the 46th IEEE/ACM International Conference on Software Engineering. ACM, Lisbon, Portugal, pp. 1–13.. <https://doi.org/10.1145/3597503.3623331>
- Dessouky, G., Gens, D., Haney, P., Persyn, G., Kanuparthi, A., Khattri, H., Fung, J.M., Sadeghi, A.-R., Rajendran, J., 2018. When a Patch Is Not Enough - HardFails: Software-Exploitable Hardware Bugs.. <https://doi.org/10.48550/arXiv.1812.00197>
- Dupriez, T., Polito, G., Costiou, S., Aranega, V., Ducasse, S., 2019. Sindarin: A Versatile Scripting API for the Pharo Debugger, in: Proceedings of the 15th ACM SIGPLAN International Symposium on Dynamic Languages, DLS 2019. Association for Computing Machinery, New York, NY, USA, pp. 67–79.. <https://doi.org/10.1145/3359619.3359745>
- Engblom, J., 2012. A Review of Reverse Debugging, in: Proceedings of the 2012 System, Software, SoC and Silicon Debug Conference. pp. 1–6.
- English, K.V., Obaidat, I., Sridhar, M., 2019. Exploiting Memory Corruption Vulnerabilities in Connman for IoT Devices, in: 2019 49th Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN). pp. 247–255.. <https://doi.org/10.1109/DSN.2019.00036>
- Espressif Systems, 2023a. ESP-IDF Programming Guide.
- Espressif Systems, 2023b. ESPRESSIF. Espressif Offers Integrated, Reliable and Energy-Efficient Wireless SoCs.
- Evans, T.G., Darley, D.L., 1966. On-Line Debugging Techniques: A Survey, in: Proceedings of the November 7-10, 1966, Fall Joint Computer Conference, AFIPS '66 (Fall). Association for Computing Machinery, New York, NY, USA, pp. 37–50.. <https://doi.org/10.1145/1464291.1464295>
- Fard, A.M., Mesbah, A., 2017. JavaScript: The (Un)Covered Parts, in: 2017 IEEE International Conference on Software Testing, Verification and Validation, ICST. IEEE, New York, NY, USA, pp. 230–240.. <https://doi.org/10.1109/ICST.2017.28>
- Fazzini, M., Orso, A., 2020. Managing App Testing Device Clouds: Issues and Opportunities, in: 2020 35th IEEE/ACM International Conference on Automated Software Engineering (ASE). pp. 1257–1259.

- Feldman, S.I., Brown, C.B., 1988. IGOR: A System for Program Debugging via Reversible Execution. ACM SIGPLAN Notices 24, 112–123.. <https://doi.org/10.1145/69215.69226>
- Felleisen, M., Findler, R.B., Flatt, M., 2009. Semantics Engineering with PLT Redex. Mit Press.
- Felleisen, M., Friedman, D.P., 1986. Control Operators, the SECD-machine, and the [1]-Calculus. Indiana University, Computer Science Department.
- Fermyon Technologies, Inc., 2023. WebAssembly Language Support Matrix.
- Ferrari, G., Tuosto, E., 2001. A Debugging Calculus for Mobile Ambients, in: Proceedings of the 2001 ACM Symposium on Applied Computing. ACM, Las Vegas Nevada USA.. <https://doi.org/10.1145/372202.380701>
- Ferreira Ruiz, F., Collins, B., al, \.e., 2024. Open Bot Brain.
- Fielding, R.T., Reschke, J., 2014. Hypertext Transfer Protocol (HTTP/1.1): Message Syntax and Routing.. <https://doi.org/10.17487/RFC7230>
- Flanagan, D., 2020. JavaScript: The Definitive Guide, 7th. ed. O'Reilly Media, Inc., Sebastopol, CA, USA.
- Frattini, F., Pietrantuono, R., Russo, S., 2016. Reproducibility of Software Bugs. Principles of Performance and Reliability Modeling and Evaluation: Essays in Honor of Kishor Trivedi on His 70th Birthday.. https://doi.org/10.1007/978-3-319-30599-8_21
- Free Software Foundation, n.d.. GDB: The GNU Project Debugger.
- Gait, J., 1986. A Probe Effect in Concurrent Programs. Software: Practice and Experience 16, 225–233.. <https://doi.org/10.1002/spe.4380160304>
- García-Ferreira, I., Laorden, C., Santos, I., Bringas, P.G., 2014. A Survey on Static Analysis and Model Checking, in: de la Puerta, J.G., Ferreira, I.G., Bringas, P.G., Klett, F., Abraham, A., de Carvalho, A.C., Herrero, Á., Baruque, B., Quintián, H., Corchado, E. (Eds.), International Joint Conference SOCO'14-CISIS'14-ICEUTE'14. Springer International Publishing, Cham, pp. 443–452.. https://doi.org/10.1007/978-3-319-07995-0_44
- George, D., 2021. MicroPython.
- Giachino, E., Lanese, I., Mezzina, C.A., 2014. Causal-Consistent Reversible Debugging, in: Gnesi, S., Rensink, A. (Eds.), Fundamental Approaches to Software Engineering, Lecture Notes in Computer Science. Springer, Berlin, Heidelberg, pp. 370–384.. https://doi.org/10.1007/978-3-642-54804-8_26

Bibliography

- Gluhak, A., Krco, S., Nati, M., Pfisterer, D., Mitton, N., Razafindralambo, T., 2011. A Survey on Facilities for Experimental Internet of Things Research. *IEEE Communications Magazine* 49, 58–67.. <https://doi.org/10.1109/MCOM.2011.6069710>
- Glück, R., Yokoyama, T., 2023. Reversible Computing from a Programming Language Perspective. *Theoretical Computer Science* 953, 113429.. <https://doi.org/10.1016/j.tcs.2022.06.010>
- Godefroid, P., 1997. Model Checking for Programming Languages Using VeriSoft, in: Proceedings of the 24th ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages, POPL '97. Association for Computing Machinery, New York, NY, USA, pp. 174–186.. <https://doi.org/10.1145/263699.263717>
- Godefroid, P., Klarlund, N., Sen, K., 2005. DART: Directed Automated Random Testing. *SIGPLAN Not.* 40, 213–223.. <https://doi.org/10.1145/1064978.1065036>
- GoogleTest, 2023. GoogleTest User's Guide.
- Gosling, J., Joy, B., Steele, G.L., 1996. The Java Language Specification, 1st ed. Addison-Wesley Longman Publishing Co., Inc., Boston, MA, USA.
- Green, B.F., 1960. IPL-V: The Newell-Shaw-Simon Programming Language. *Behavioral Science* 5, 94–100.
- Guerraoui, R., 1999. What Object-Oriented Distributed Programming Does Not Have to Be, and What It May Be. *Informatik*.
- Gupta, D., Jalote, P., Barua, G., 1996. A Formal Framework for On-Line Software Version Change. *IEEE Transactions on Software Engineering* 22, 120–131.. <https://doi.org/10.1109/32.485222>
- Gupta, P., M, I.O.P., 2021. A Survey of Application Layer Protocols for Internet of Things, in: 2021 International Conference on Communication Information and Computing Technology (ICCICT). pp. 1–6.. <https://doi.org/10.1109/ICCICT50803.2021.9510140>
- Gurdeep Singh, R., 2022. Taming Nondeterminism : Programming Language Abstractions and Tools for Dealing with Nondeterministic Programs.
- Gurdeep Singh, R., Scholliers, C., 2019. WARDuino: A Dynamic WebAssembly Virtual Machine for Programming Microcontrollers, in: Proceedings of the 16th ACM SIGPLAN International Conference on Managed Programming Languages and Runtimes, MPLR 2019. Association for Computing Machinery, New York, NY, USA, pp. 27–36.. <https://doi.org/10.1145/3357390.3361029>

Gurdeep Singh, R., Torres Lopez, C., Marr, S., Gonzalez Boix, E., Scholliers, C., 2019. Multiverse Debugging: Non-Deterministic Debugging for Non-Deterministic Programs (Artifact). Dagstuhl Artifacts Series 5, 1–3.. <https://doi.org/10.4230/DARTS.5.2.4>

Haas, A., Rossberg, A., Schuff, D.L., Titzer, B.L., Holman, M., Gohman, D., Wagner, L., Zakai, A., Bastien, J., 2017. Bringing the Web up to Speed with WebAssembly, in: Proceedings of the 38th ACM SIGPLAN Conference on Programming Language Design and Implementation, PLDI 2017. Association for Computing Machinery, New York, NY, USA, pp. 185–200.. <https://doi.org/10.1145/3062341.3062363>

Haleby, J., n.d.. Awaityility.

Hambarde, P., Varma, R., Jha, S., 2014. The Survey of Real Time Operating System: RTOS, in: 2014 International Conference on Electronic Systems, Signal Processing and Computing Technologies. pp. 34–39.. <https://doi.org/10.1109/ICESC.2014.15>

Hanford, K.V., 1960. The Share Operating System for the IBM 709. Annual Review in Automatic Programming 1, 169–177.. [https://doi.org/10.1016/0066-4138\(60\)90039-2](https://doi.org/10.1016/0066-4138(60)90039-2)

Harman, M., O'Hearn, P., 2018. From Start-ups to Scale-ups: Opportunities and Open Problems for Static and Dynamic Program Analysis, in: 2018 IEEE 18th International Working Conference on Source Code Analysis and Manipulation (SCAM). pp. 1–23.. <https://doi.org/10.1109/SCAM.2018.00009>

Haulund, T., Mogensen, T.Æ., Glück, R., 2017. Implementing Reversible Object-Oriented Language Features on Reversible Machines, in: Phillips, I., Rahaman, H. (Eds.), Reversible Computation. Springer International Publishing, Cham, pp. 66–73.. https://doi.org/10.1007/978-3-319-59936-6_5

Hay-Schmidt, L., Glück, R., Cserveska, M.H., Haulund, T., 2021. Towards a Unified Language Architecture for Reversible Object-Oriented Programming, in: Yamashita, S., Yokoyama, T. (Eds.), Reversible Computation. Springer International Publishing, Cham, pp. 96–106.. https://doi.org/10.1007/978-3-030-79837-6_6

Herlihy, M.P., Wing, J.M., 1990. Linearizability: A Correctness Condition for Concurrent Objects. ACM Trans. Program. Lang. Syst. 12, 463–492.. <https://doi.org/10.1145/78969.78972>

Heunen, C., Karvonen, M., 2015. Reversible Monadic Computing. Electronic Notes in Theoretical Computer Science, The 31st Conference on the

Bibliography

- Mathematical Foundations of Programming Semantics (MFPS XXXI). 319, 217–237.. <https://doi.org/10.1016/j.entcs.2015.12.014>
- Hickey, P., Konka, J., Gohman, D., Clegg, S., Brown, A., Crichton, A., Clark, L., Ihrig, C., Huene, P., Yuji, \.Y., Vasilik, D., Triplett, J., Rubanov, S., Akbary, S., Frysinger, M., Turner, A., Zakai, A., Mackenzie, A., Brittain, B., Beyer, C., McKay, D., Wang, L., Mielniczuk, M., Berger, M., PTrottier, Sikora, P., Schneidereit, T., martin, k., nasso, 2020. WebAssembly/WASI: Snapshot-01.. <https://doi.org/10.5281/zenodo.4323447>
- Hoey, J., Ulidowski, I., Yuen, S., 2018. Reversing Parallel Programs with Blocks and Procedures.. <https://doi.org/10.48550/arXiv.1808.08651>
- Holter, K., Hennoste, J.O., Lam, P., Saan, S., Vojdani, V., 2024. Abstract Debuggers: Exploring Program Behaviors Using Static Analysis Results, in: Proceedings of the 2024 ACM SIGPLAN International Symposium on New Ideas, New Paradigms, And Reflections on Programming and Software, Onward! '24. Association for Computing Machinery, New York, NY, USA, pp. 130–146.. <https://doi.org/10.1145/3689492.3690053>
- Huang, J.-f., 2014. AppACTS: Mobile App Automated Compatibility Testing Service, in: 2014 2nd IEEE International Conference on Mobile Cloud Computing, Services, And Engineering. pp. 85–90.. <https://doi.org/10.1109/MobileCloud.2014.13>
- Huang, W., Wang Xin, 2021. WebAssembly Micro Runtime.
- Hunt, A., Thomas, D., 1999. The Pragmatic Programmer. Addison-Wesley.
- Högl, H., Rath, D., 2006. Open On-Chip Debugger—Openocd—. Fakultat fur Informatik, Tech. Rep.
- IEEE Standard for Test Access Port and Boundary-Scan Architecture, 2013. . IEEE Std 1149.1-2013 (Revision of IEEE Std 1149.1-2001) 1–444.. <https://doi.org/10.1109/IEEEESTD.2013.6515989>
- Ierusalimschy, R., de Figueiredo, L.H., Filho, W.C., 1996. Lua—An Extensible Extension Language. Software: Practice and Experience 26, 635–652.. [https://doi.org/10.1002/\(SICI\)1097-024X\(199606\)26:6<635::AID-SPE26>3.0.CO;2-P](https://doi.org/10.1002/(SICI)1097-024X(199606)26:6<635::AID-SPE26>3.0.CO;2-P)
- IFS Institut für Software, 2023. CUTE. C++ Unit Testing Easier.
- Iqbal, M.Z., Arcuri, A., Briand, L., 2015. Environment Modeling and Simulation for Automated Testing of Soft Real-Time Embedded Software. Software & Systems Modeling 14, 483–524.. <https://doi.org/10.1007/s10270-013-0328-6>

- Jacoby, K., Layton, H., 1961. Automation of Program Debugging, in: Proceedings of the 1961 16th ACM National Meeting, ACM '61. Association for Computing Machinery, New York, NY, USA, p. 123.. <https://doi.org/10.1145/800029.808556>
- Jangda, A., Powers, B., Berger, E.D., Guha, A., 2019. Not So Fast: Analyzing the Performance of {\vphantom {}}WebAssembly\vphantom {} vs. Native Code, in: 2019 USENIX Annual Technical Conference (USENIX ATC 19). pp. 107–120.
- Jard, C., Jéron, T., Tanguy, L., Viho, C., 1999. Remote Testing Can Be as Powerful as Local Testing. Formal Methods for Protocol Engineering and Distributed Systems: FORTE XII / PSTV XIX'99 IFIP TC6 WG6.1 Joint International Conference on Formal Description Techniques for Distributed Systems and Communication Protocols (FORTE XII) and Protocol Specification, Testing and Verification (PSTV XIX) October 5–8, 1999, Beijing, China.. https://doi.org/10.1007/978-0-387-35578-8_2
- JetBrains s.r.o., 2023. WebStorm. The Smartest JavaScript IDE.
- Jhala, R., Majumdar, R., 2009. Software Model Checking. ACM Comput. Surv. 41, 1–54.. <https://doi.org/10.1145/1592434.1592438>
- Johnson, M., 1981. Dispel: A Run-Time Debugging Language. Computer Languages 6, 79–94.. [https://doi.org/10.1016/0096-0551\(81\)90068-0](https://doi.org/10.1016/0096-0551(81)90068-0)
- The JUnit Team, n.d.. JUnit 5.
- Kahlon, V., Wang, C., Gupta, A., 2009. Monotonic Partial Order Reduction: An Optimal Symbolic Partial Order Reduction Technique, in: Bouajjani, A., Maler, O. (Eds.), Computer Aided Verification. Springer, Berlin, Heidelberg, pp. 398–413.. https://doi.org/10.1007/978-3-642-02658-4_31
- Kanstrén, T., Mäkelä, J., Karhula, P., 2018. Architectures and Experiences in Testing IoT Communications, in: Proceedings - 2018 IEEE 11th International Conference on Software Testing, Verification and Validation Workshops, ICSTW 2018. pp. 98–103.. <https://doi.org/10.1109/ICSTW.2018.00034>
- Karmios, N., Ayoun, S.-É., Gardner, P., 2023. Symbolic Debugging with Gillian, in: Proceedings of the 1st ACM International Workshop on Future Debugging Techniques, DEBT 2023. Association for Computing Machinery, New York, NY, USA, pp. 1–2.. <https://doi.org/10.1145/3605155.3605861>
- Keahey, K., Anderson, J., Zhen, Z., Riteau, P., Ruth, P., Stanzione, D., Cevik, M., Colleran, J., Gunawi, H.S., Hammock, C., Mambretti, J., Barnes,

Bibliography

- A., Halbah, F., Rocha, A., Stubbs, J., 2020. Lessons Learned from the Chameleon Testbed, in: 2020 USENIX Annual Technical Conference (USENIX ATC 20). pp. 219–233.
- Kelly, F., 1981. Reversibility and Stochastic Networks / F.P. Kelly. SERBIULA (sistema Librum 2.0) 76.. <https://doi.org/10.2307/2287860>
- Kemeny, J.G., Kurtz, T.E., Cochran, D.S., 1968. Basic: A Manual for BASIC, the Elementary Algebraic Language Designed for Use with the Dartmouth Time Sharing System. Dartmouth Publications.
- Kennedy, H.C., 1974. Peano's Concept of Number. Historia Mathematica 1, 387–408.. [https://doi.org/10.1016/0315-0860\(74\)90031-7](https://doi.org/10.1016/0315-0860(74)90031-7)
- Kernighan, B.W., Ritchie, D.M., 1989. The C Programming Language. Prentice Hall Press, USA.
- Kery, M.B., Myers, B.A., 2017. Exploring Exploratory Programming, in: 2017 IEEE Symposium on Visual Languages and Human-Centric Computing (VL/HCC). pp. 25–29.. <https://doi.org/10.1109/VLHCC.2017.8103446>
- Kery, M.B., Radensky, M., Arya, M., John, B.E., Myers, B.A., 2018. The Story in the Notebook: Exploratory Data Science Using a Literate Programming Tool, in: Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, CHI '18. Association for Computing Machinery, New York, NY, USA, pp. 1–11.. <https://doi.org/10.1145/3173574.3173748>
- Khan, M.Z., Askwith, B., Bouhafs, F., Asim, M., 2011. Limitations of Simulation Tools for Large-Scale Wireless Sensor Networks, in: 2011 IEEE Workshops of International Conference on Advanced Information Networking and Applications. IEEE, New York, NY, USA, pp. 820–825.. <https://doi.org/10.1109/WAINA.2011.59>
- Kim, H., Ahmad, A., Hwang, J., Baqa, H., Le Gall, F., Reina Ortega, M.A., Song, J., 2018. IoT-TaaS: Towards a Prospective IoT Testing Framework. IEEE Access 6, 15480–15493.. <https://doi.org/10.1109/ACCESS.2018.2802489>
- King, J.C., 1976. Symbolic Execution and Program Testing. Communications of the ACM 19, 385–394.. <https://doi.org/10.1145/360248.360252>
- Klimushenkova, M.A., Dovgalyuk, P.M., 2017. Improving the Performance of Reverse Debugging. Programming and Computer Software 43, 60–66.. <https://doi.org/10.1134/S0361768817010042>
- Koji, Y., others, 2023. Mruby-Arduino. Mruby-Arduino Is Wrapper Mrbgem for Arduino API.

- Kong, P., Li, L., Gao, J., Liu, K., Bissyandé, T.F., Klein, J., 2019. Automated Testing of Android Apps: A Systematic Literature Review. *IEEE Transactions on Reliability* 68, 45–66.. <https://doi.org/10.1109/TR.2018.2865733>
- Kopetz, H., Ochsenreiter, W., 1987. Clock Synchronization in Distributed Real-Time Systems. *IEEE Transactions on Computers* 933–940.. <https://doi.org/10.1109/TC.1987.5009516>
- Krekel, H., team, p.-d., 2023. Pytest: Helps You Write Better Programs.
- Kurshan, R., Levin, V., Minea, M., Peled, D., Yenigün, H., 1998. Static Partial Order Reduction, in: Steffen, B. (Ed.), *Tools and Algorithms for the Construction and Analysis of Systems*. Springer, Berlin, Heidelberg, pp. 345–357.. <https://doi.org/10.1007/BFb0054182>
- Lam, W., Godefroid, P., Nath, S., Santhiar, A., Thummalapenta, S., 2019. Root Causing Flaky Tests in a Large-Scale Industrial Setting, in: *Proceedings of the 28th ACM SIGSOFT International Symposium on Software Testing and Analysis, Issta 2019*. Association for Computing Machinery, New York, NY, USA, pp. 101–111.. <https://doi.org/10.1145/3293882.3330570>
- Lami, P., Lanese, I., Stefani, J.-B., 2024. A Small-Step Semantics for~Janus, in: Mogensen, T.Æ., Mikulski, Ł. (Eds.), *Reversible Computation*. Springer Nature Switzerland, Cham, pp. 105–123.. https://doi.org/10.1007/978-3-031-62076-8_8
- Lamport, 1979. How to Make a Multiprocessor Computer That Correctly Executes Multiprocess Programs. *IEEE Transactions on Computers* 690–691.. <https://doi.org/10.1109/TC.1979.1675439>
- Lamport, L., 1978. Time, Clocks, and the Ordering of Events in a Distributed System. *Commun. ACM* 21, 558–565.. <https://doi.org/10.1145/359545.359563>
- Lanese, I., 2018. From Reversible Semantics to Reversible Debugging, in: Kari, J., Ulidowski, I. (Eds.), *Reversible Computation, Lecture Notes in Computer Science*. Springer International Publishing, Cham, pp. 34–46.. https://doi.org/10.1007/978-3-319-99498-7_2
- Lanese, I., Mezzina, C., Tiezzi, F., 2014. Causal-Consistent Reversibility.
- Lanese, I., Nishida, N., Palacios, A., Vidal, G., 2018. CauDER: A Causal-Consistent Reversible Debugger for Erlang, in: Gallagher, J.P., Sulzmann, M. (Eds.), *Functional and Logic Programming, Lecture Notes in Computer Science*. Springer International Publishing, Cham, pp. 247–263.. https://doi.org/10.1007/978-3-319-90686-7_16

Bibliography

- Laursen, J.S., Ellekilde, L.-P., Schultz, U.P., 2018. Modelling Reversible Execution of Robotic Assembly. *Robotica* 36, 625–654.. <https://doi.org/10.1017/S0263574717000613>
- Lauwaerts, T., Castillo, C.R., Singh, R.G., Marra, M., Scholliers, C., Gonzalez Boix, E., 2022. Event-Based Out-of-Place Debugging, in: Proceedings of the 19th International Conference on Managed Programming Languages and Runtimes, MPLR '22. Association for Computing Machinery, New York, NY, USA, pp. 85–97.. <https://doi.org/10.1145/3546918.3546920>
- Lauwaerts, T., Singh, R.G., Scholliers, C., 2024. WARDuino: An Embedded WebAssembly Virtual Machine. *Journal of Computer Languages* 101268.. <https://doi.org/10.1016/j.cola.2024.101268>
- Lea, D., 1997. Design for Open Systems in Java, in: Garlan, D., Le Métayer, D. (Eds.), *Coordination Languages and Models*. Springer, Berlin, Heidelberg, pp. 32–45.. https://doi.org/10.1007/3-540-63383-9_71
- Lee, K., Lee, Y., Lee, H., Yim, K., 2016. A Brief Review on JTAG Security, in: 2016 10th International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing (IMIS). pp. 486–490.. <https://doi.org/10.1109/IMIS.2016.102>
- Leeman, G.B., 1986. A Formal Approach to Undo Operations in Programming Languages. *ACM Transactions on Programming Languages and Systems* 8, 50–87.. <https://doi.org/10.1145/5001.5005>
- Lehmann, D., Kinder, J., Pradel, M., 2020. Everything Old Is New Again: Binary Security of Webassembly, in: Proceedings of the 29th USENIX Conference on Security Symposium, SEC'20. USENIX Association, USA, pp. 217–234.
- Levis, P., Culler, D., 2002. Maté: A Tiny Virtual Machine for Sensor Networks, in: Proceedings of the 10th International Conference on Architectural Support for Programming Languages and Operating Systems, ASPLOS X. Association for Computing Machinery, New York, NY, USA, pp. 85–95.. <https://doi.org/10.1145/605397.605407>
- Lewis, B., 2003. Debugging Backwards in Time.. <https://doi.org/10.48550/arXiv.cs/0310016>
- Li, C., Chen, R., Wang, B., Wang, Z., Yu, T., Jiang, Y., Gu, B., Yang, M., 2023. An Empirical Study on Concurrency Bugs in Interrupt-Driven Embedded Software, in: Proceedings of the 32nd ACM SIGSOFT International Symposium on Software Testing and Analysis, ISSTA 2023. Association for Computing Machinery, New York, NY, USA, pp. 1345–1356.. <https://doi.org/10.1145/3597926.3598140>

- Li, H., Xu, Y., Wu, F., Yin, C., 2009. Research of "Stub" Remote Debugging Technique, in: 2009 4th International Conference on Computer Science & Education. pp. 990–994.. <https://doi.org/10.1109/ICCSE.2009.5228140>
- Li, W., Li, N., 2012. A Formal Semantics for Program Debugging. *Science China Information Sciences* 55, 133–148.. <https://doi.org/10.1007/s11432-011-4530-2>
- Licklider, J.C.R., Clark, W.E., 1962. On-Line Man-Computer Communication, in: Proceedings of the May 1-3, 1962, Spring Joint Computer Conference, AIEE-IRE '62(Spring). Association for Computing Machinery, New York, NY, USA, pp. 113–128.. <https://doi.org/10.1145/1460833.1460847>
- Lieberman, H., 1997. The Debugging Scandal and What to Do about It.. *Communications of the ACM* 40, 26–30.
- Lieberman, H., 1997. ZStep 95: A Reversible, Animated Source Code Stepper. *Software Visualization: Programming as a Multimedia Experience*.
- Lu, S., Park, S., Seo, E., Zhou, Y., 2008. Learning from Mistakes: A Comprehensive Study on Real World Concurrency Bug Characteristics, in: Proceedings of the 13th International Conference on Architectural Support for Programming Languages and Operating Systems, ASPLOS XIII. Association for Computing Machinery, New York, NY, USA, pp. 329–339.. <https://doi.org/10.1145/1346281.1346323>
- Lubbers, M., Koopman, P., Plasmeijer, R., 2021. Interpreting Task Oriented Programs on Tiny Computers, in: Proceedings of the 31st Symposium on Implementation and Application of Functional Languages, IFL '19. Association for Computing Machinery, New York, NY, USA, pp. 1–12.. <https://doi.org/10.1145/3412932.3412936>
- Lutz, C., Derby, H., 1986. Janus: A Time-Reversible Language. Letter to R. Landauer 2.
- Madsen, M., Lhoták, O., Tip, F., 2017. A Model for Reasoning about JavaScript Promises. *Proc. ACM Program. Lang.* 1, 1–24.. <https://doi.org/10.1145/3133910>
- Makhshari, A., Mesbah, A., 2021. IoT Bugs and Development Challenges, in: 2021 IEEE/ACM 43rd International Conference on Software Engineering (ICSE). pp. 460–472.. <https://doi.org/10.1109/ICSE43902.2021.00051>
- Maksimovic, M., Vujošić, V., Davidović, N., Milosević, V., Perišić, B., 2014. Raspberry Pi as Internet of Things Hardware: Performances and Constraints, in: Proceedings of the 1st International Conference on Electrical, Electronic and Computing Engineering.

Bibliography

- Maloney, J., Resnick, M., Rusk, N., Silverman, B., Eastmond, E., 2010. The Scratch Programming Language and Environment. *ACM Transactions on Computing Education* 10, 1–15.. <https://doi.org/10.1145/1868358.1868363>
- Mani, S.K., Durairajan, R., Barford, P., Sommers, J., 2018. An Architecture for IoT Clock Synchronization, in: Proceedings of the 8th International Conference on the Internet of Things, IOT '18. Association for Computing Machinery, New York, NY, USA, pp. 1–8.. <https://doi.org/10.1145/3277593.3277606>
- Marceau, G., Cooper, G., Spiro, J., Krishnamurthi, S., Reiss, S., 2007. The Design and Implementation of a Dataflow Language for Scriptable Debugging. *Automated Software Engineering* 14, 59–86.. <https://doi.org/10.1007/s10515-006-0003-z>
- Marques, F., Fragoso Santos, J., Santos, N., Adão, P., 2022. Concolic Execution for WebAssembly, in: Ali, K., Vitek, J. (Eds.), 36th European Conference on Object-Oriented Programming (ECOOP 2022), Leibniz International Proceedings in Informatics (LIPIcs). Schloss Dagstuhl – Leibniz-Zentrum für Informatik, Dagstuhl, Germany, pp. 1–29.. <https://doi.org/10.4230/LIPIcs.ECOOP.2022.11>
- Marra, M., Polito, G., Gonzalez Boix, E., 2018. Out-Of-Place Debugging: A Debugging Architecture to Reduce Debugging Interference. *The Art, Science, and Engineering of Programming* 3, 1–29.. <https://doi.org/10.22152/programming-journal.org/2019/3/3>
- Massey, S., Shymanskyy, V., 2022. M3.
- Massey, S., Shymanskyy, V., 2021. WASM3.
- Matsuda, K., Wang, M., 2020. Sparcl: A Language for Partially-Invertible Computation. *Proceedings of the ACM on Programming Languages* 4, 1–31.. <https://doi.org/10.1145/3409000>
- McBride, J., 1989. Electrical Contact Bounce in Medium-Duty Contacts. *IEEE Transactions on Components, Hybrids, and Manufacturing Technology* 12, 82–90.. <https://doi.org/10.1109/33.19016>
- McCauley, R., Fitzgerald, S., Lewandowski, G., Murphy, L., Simon, B., Thomas, L., Zander, C., 2008. Debugging: A Review of the Literature from an Educational Perspective. *Computer Science Education* 18, 67–92.. <https://doi.org/10.1080/08993400802114581>
- McDonald, C., others, 2023. Mruby-Esp32-System. System Library for Mruby-Esp32.

- McDowell, C.E., Helmbold, D.P., 1989. Debugging Concurrent Programs. ACM Comput. Surv. 21, 593–622.. <https://doi.org/10.1145/76894.76897>
- Medhat, N., Moussa, S.M., Badr, N.L., Tolba, M.F., 2020. A Framework for Continuous Regression and Integration Testing in IoT Systems Based on Deep Learning and Search-Based Techniques. IEEE Access 8, 215716–215726.. <https://doi.org/10.1109/ACCESS.2020.3039931>
- Mezzina, C.A., Schlatte, R., Glück, R., Haulund, T., Hoey, J., Holm Cservenka, M., Lanese, I., Mogensen, T.Æ., Siljak, H., Schultz, U.P., Ulidowski, I., 2020. Software and Reversible Systems: A~Survey of Recent Activities. Reversible Computation: Extending Horizons of Computing: Selected Results of the COST Action IC1405, Lecture Notes in Computer Science.. https://doi.org/10.1007/978-3-030-47361-7_2
- Microsoft, 2023. The TypeScript Handbook.
- Mihalčík, F., Trnútč, M., Hren, A., 2022. Hardware-in-the-Loop Simulations: A Historical Overview of Engineering Challenges. Electronics 11, 2462.. <https://doi.org/10.3390/electronics11152462>
- Mikejo5000, 2025. Remote Debugging - Visual Studio (Windows).
- Mishra, B., Kertesz, A., 2020. The Use of MQTT in M2M and IoT Systems: A Survey. IEEE Access 8, 201071–201086.. <https://doi.org/10.1109/ACCESS.2020.3035849>
- Mogul, J.C., 2006. Emergent (Mis)Behavior vs. Complex Software Systems. SIGOPS Oper. Syst. Rev. 40, 293–304.. <https://doi.org/10.1145/1218063.1217964>
- Mukhin, V., Kornaga, Y., Bazaka, Y., Krylov, I., Barabash, A., Yakovleva, A., Mukhin, O., 2021. The Testing Mechanism for Software and Services Based on Mike Cohn's Testing Pyramid Modification, in: Proceedings of the 11th IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications, IDAACS 2021. pp. 589–595.. <https://doi.org/10.1109/IDAACS53288.2021.9660999>
- Murdoch, M., 2023. ArduinoUnit.
- Naik, N., 2017. Choice of Effective Messaging Protocols for IoT Systems: MQTT, CoAP, AMQP and HTTP, in: 2017 IEEE International Systems Engineering Symposium (ISSE). pp. 1–7.. <https://doi.org/10.1109/SysEng.2017.8088251>
- nanoFramework Contributors, 2021.NET nanoFramework Documentation.

Bibliography

- Nikolaidis, F., Marazakis, M., Bilas, A., 2021. IOTier: A Virtual Testbed to Evaluate Systems for IoT Environments, in: Proceedings - 21st IEEE/ACM International Symposium on Cluster, Cloud and Internet Computing, CCGGrid 2021. pp. 676–683.. <https://doi.org/10.1109/CCGrid51090.2021.00081>
- O'Callahan, R., Jones, C., Froyd, N., Huey, K., Noll, A., Partush, N., 2017. Engineering Record and Replay for Deployability, in: 2017 USENIX Annual Technical Conference (USENIX ATC 17). pp. 377–389.
- Olsson, R.A., Crawford, R.H., Ho, W.W., 1990. Dalek: A GNU, Improved Programmable Debugger., in: USENIX Technical Conference. The USENIX Association, Berkeley, CA, USA, pp. 221–231.
- OpenJS Foundation, n.d.. Mocha - the Fun, Simple, Flexible JavaScript Test Framework.
- Ozcan, M.O., Odaci, F., Ari, I., 2019. Remote Debugging for Containerized Applications in Edge Computing Environments, in: 2019 IEEE International Conference on Edge Computing (EDGE). pp. 30–32.. <https://doi.org/10.1109/EDGE.2019.00021>
- Pacheco, D., 2011. Postmortem Debugging in Dynamic Environments. Commun. ACM 54, 44–51.. <https://doi.org/10.1145/2043174.2043189>
- Pan, R., Bagherzadeh, M., Ghaleb, T.A., Briand, L., 2021. Test Case Selection and Prioritization Using Machine Learning: A Systematic Literature Review. Empirical Software Engineering 27, 29.. <https://doi.org/10.1007/s10664-021-10066-6>
- Parker, D., 2015. JavaScript with Promises, 1st ed. O'Reilly Media, Inc.
- Parry, O., Kapfhammer, G.M., Hilton, M., McMinn, P., 2021. A Survey of Flaky Tests. ACM Trans. Softw. Eng. Methodol. 31, 1–74.. <https://doi.org/10.1145/3476105>
- Pasquier, M., Teodorov, C., Jouault, F., Brun, M., Lagadec, L., 2023a. Debugging Paxos in the UML Multiverse, in: 2023 ACM/IEEE International Conference on Model Driven Engineering Languages and Systems Companion (MODELS-C). pp. 811–820.. <https://doi.org/10.1109/MODELS-C59198.2023.00130>
- Pasquier, M., Teodorov, C., Jouault, F., Brun, M., Le Roux, L., Lagadec, L., 2023b. Temporal Breakpoints for Multiverse Debugging, in: Proceedings of the 16th ACM SIGPLAN International Conference on Software Language Engineering, SLE 2023. Association for Computing Machin-

- ery, New York, NY, USA, pp. 125–137.. <https://doi.org/10.1145/3623476.3623526>
- Pasquier, M., Teodorov, C., Jouault, F., Brun, M., Roux, L.L., Lagadec, L., 2022. Practical Multiverse Debugging through User-Defined Reductions: Application to UML Models, in: Proceedings of the 25th International Conference on Model Driven Engineering Languages and Systems, MODELS '22. Association for Computing Machinery, New York, NY, USA, pp. 87–97.. <https://doi.org/10.1145/3550355.3552447>
- Peano, G., 1891. Sul Concetto Di Numero. *Rivista Matematica* 1, 256–267.
- Peress, Y., Nashif, A., Brunnen, M., Andersen, H.B., Emelchenko, A., Massey, A.E., Bolivar, M., Olivares, I.H., 2024. Test Framework — Zephyr Project Documentation.
- Perez, F., Granger, B.E., 2007. IPython: A System for Interactive Scientific Computing. *Computing in Science & Engineering* 9, 21–29.. <https://doi.org/10.1109/MCSE.2007.53>
- Perrin, M., Mostefaoui, A., Jard, C., 2016. Causal Consistency: Beyond Memory, in: Proceedings of the 21st ACM SIGPLAN Symposium on Principles and Practice of Parallel Programming, PPoPP '16. Association for Computing Machinery, New York, NY, USA, pp. 1–12.. <https://doi.org/10.1145/2851141.2851170>
- Perscheid, M., Siegmund, B., Taeumel, M., Hirschfeld, R., 2017. Studying the Advancement in Debugging Practice of Professional Software Developers. *Software Quality Journal* 25, 83–110.. <https://doi.org/10.1007/s11219-015-9294-2>
- Phipps-Costin, L., Rossberg, A., Guha, A., Leijen, D., Hillerström, D., Sivaramakrishnan, \.K., Pretnar, M., Lindley, S., 2023. Continuing WebAssembly with Effect Handlers. *Proceedings of the ACM on Programming Languages* 7, 460–485.. <https://doi.org/10.1145/3622814>
- Pierce, B.C., 2002. Types and Programming Languages, 1st ed. The MIT Press.
- Plasmeijer, R., Lijnse, B., Michels, S., Achter, P., Koopman, P., 2012. Task-Oriented Programming in a Pure Functional Language, in: Proceedings of the 14th Symposium on Principles and Practice of Declarative Programming, PPDP '12. Association for Computing Machinery, New York, NY, USA, pp. 195–206.. <https://doi.org/10.1145/2370776.2370801>
- PlatformIO, 2023a. Unity.
- PlatformIO, 2023b. Unit Testing.

Bibliography

- Plotkin, G., Pretnar, M., 2009. Handlers of Algebraic Effects, in: Castagna, G. (Ed.), Programming Languages and Systems, Lecture Notes in Computer Science. Springer, Berlin, Heidelberg, pp. 80–94.. https://doi.org/10.1007/978-3-642-00590-9_7
- Popereshnyak, S., Suprun, O., Suprun, O., Wieckowski, T., 2018. IoT Application Testing Features Based on the Modelling Network, in: International Conference on Perspective Technologies and Methods in MEMS Design. pp. 127–131.. <https://doi.org/10.1109/MEMSTECH.2018.8365717>
- Pothier, G., Tanter, É., 2009. Back to the Future: Omniscient Debugging. IEEE Software 26, 78–85.. <https://doi.org/10.1109/MS.2009.169>
- Pothier, G., Tanter, É., Piquer, J., 2007. Scalable Omniscient Debugging. SIGPLAN Not. 42, 535–552.. <https://doi.org/10.1145/1297105.1297067>
- Python Software Foundation, n.d.. Doctest — Test Interactive Python Examples.
- Pötsch, A., Haslhofer, F., Springer, A., 2017. Advanced Remote Debugging of LoRa-enabled IoT Sensor Nodes, in: Proceedings of the Seventh International Conference on the Internet of Things, IoT '17. Association for Computing Machinery, New York, NY, USA, pp. 1–2.. <https://doi.org/10.1145/3131542.3140259>
- Ramprasad, B., Fokaefs, M., Mukherjee, J., Litoiu, M., 2019. EMU-IoT-A Virtual Internet of Things Lab, in: Proceedings - 2019 IEEE International Conference on Autonomic Computing, ICAC 2019. pp. 73–83.. <https://doi.org/10.1109/ICAC.2019.00019>
- Rather, E.D., Moore, C.H., 1976. The FORTH Approach to Operating Systems, in: Proceedings of the 1976 Annual Conference, ACM '76. Association for Computing Machinery, New York, NY, USA, pp. 233–240.. <https://doi.org/10.1145/800191.805586>
- Remote Debugging - LLDB, n.d.
- Robot Framework Foundation, 2023. Robot Framework.
- Rodriguez, M., Piattini, M., Ebert, C., 2019. Software Verification and Validation Technologies and Tools. IEEE Software 36, 13–24.. <https://doi.org/10.1109/MS.2018.2883354>
- Rojas Castillo, C., Marra, M., Bauwens, J., Gonzalez Boix, E., 2021. WOOD: Extending a WebAssembly VM with Out-of-Place Debugging for IoT Applications. WOOD: Extending a WebAssembly VM with Out-of-Place Debugging for IoT applications.

- Ronsse, M., De Bosschere, K., 1999. RecPlay: A Fully Integrated Practical Record/Replay System. *ACM Transactions on Computer Systems* 17, 133–152.. <https://doi.org/10.1145/312203.312214>
- Rosenberg, J.B., 1996. How Debuggers Work: Algorithms, Data Structures, and Architecture. John Wiley & Sons, Inc., USA.
- Roska, T., 1990. Limitations and Complexity of Digital Hardware Simulators Used for Large-Scale Analogue Circuit and System Dynamics. *International Journal of Circuit Theory and Applications* 18, 11–21.. <https://doi.org/10.1002/cta.4490180104>
- Rospocher, M., Ghidini, C., Serafini, L., 2014. An Ontology for the Business Process Modelling Notation. *Frontiers in Artificial Intelligence and Applications* 267, 133–146.. <https://doi.org/10.3233/978-1-61499-438-1-133>
- Rossberg, A., 2023. WebAssembly (Release 2.0).
- Rossberg, A., 2019. WebAssembly (Release 1.0).
- Rossum, G., 1995. Python Reference Manual. Amsterdam, The Netherlands, The Netherlands.
- Saeedi, M., Markov, I.L., 2013. Synthesis and Optimization of Reversible Circuits—a Survey. *ACM Comput. Surv.* 45, 1–34.. <https://doi.org/10.1145/2431211.2431220>
- Salvanesci, G., Mezini, M., 2016. Debugging for Reactive Programming, in: Proceedings of the 38th International Conference on Software Engineering, ICSE '16. Association for Computing Machinery, New York, NY, USA, pp. 796–807.. <https://doi.org/10.1145/2884781.2884815>
- Schmuck, F., Cristian, F., 1990. Continuous Clock Amortization Need Not Affect the Precision of a Clock Synchronization Algorithm, in: Proceedings of the Ninth Annual ACM Symposium on Principles of Distributed Computing, PODC '90. Association for Computing Machinery, New York, NY, USA, pp. 133–143.. <https://doi.org/10.1145/93385.93411>
- Schordan, M., Oppelstrup, T., Jefferson, D., Barnes, P.D., Quinlan, D., 2016. Automatic Generation of Reversible C++ Code and Its Performance in a Scalable Kinetic Monte-Carlo Application, in: Proceedings of the 2016 ACM SIGSIM Conference on Principles of Advanced Discrete Simulation, SIGSIM-PADS '16. Association for Computing Machinery, New York, NY, USA, pp. 111–122.. <https://doi.org/10.1145/2901378.2901394>
- Schroeder, B., Pinheiro, E., Weber, W.-D., 2009. DRAM Errors in the Wild: A Large-Scale Field Study. *SIGMETRICS Perform. Eval. Rev.* 37, 193–204.. <https://doi.org/10.1145/2492101.1555372>

Bibliography

- Schultz, U.P., 2020. Reversible Control of Robots. *Reversible Computation: Extending Horizons of Computing: Selected Results of the COST Action IC1405..* https://doi.org/10.1007/978-3-030-47361-7_8
- Schultz, U.P., Axelsen, H.B., 2016. Elements of a Reversible Object-Oriented Language, in: Devitt, S., Lanese, I. (Eds.), *Reversible Computation*. Springer International Publishing, Cham, pp. 153–159.. https://doi.org/10.1007/978-3-319-40578-0_10
- Sen, K., Agha, G., 2006. Automated Systematic Testing of Open Distributed Programs, in: Baresi, L., Heckel, R. (Eds.), *Fundamental Approaches to Software Engineering*. Springer, Berlin, Heidelberg, pp. 339–356.. https://doi.org/10.1007/11693017_25
- Shapiro, E.Y., 1983. *Algorithmic Program Debugging*. The MIT Press.. <https://doi.org/10.7551/mitpress/1192.001.0001>
- Shapiro, M., Preguiça, N., Baquero, C., Zawirski, M., 2011. Conflict-Free Replicated Data Types, in: Défago, X., Petit, F., Villain, V. (Eds.), *Stabilization, Safety, And Security of Distributed Systems*. Springer, Berlin, Heidelberg, pp. 386–400.. https://doi.org/10.1007/978-3-642-24550-3_29
- Shi, A., Lam, W., Oei, R., Xie, T., Marinov, D., 2019. iFixFlakies: A Framework for Automatically Fixing Order-Dependent Flaky Tests, in: Proceedings of the 2019 27th ACM Joint Meeting on European Software Engineering Conference and Symposium on the Foundations of Software Engineering, ESEC/FSE 2019. Association for Computing Machinery, New York, NY, USA, pp. 545–555.. <https://doi.org/10.1145/3338906.3338925>
- Shymanskyy, V., 2023. Wasm3/Wasm-Debug.
- Sidna, J., Amine, B., Abdallah, N., El Alami, H., 2020. Analysis and Evaluation of Communication Protocols for IoT Applications, in: Proceedings of the 13th International Conference on Intelligent Systems: Theories and Applications, SITA'20. Association for Computing Machinery, New York, NY, USA, pp. 1–6.. <https://doi.org/10.1145/3419604.3419754>
- Skvařc Bőžić, G., Irigoyen Ceberio, I., Mayer, A., 2024. In-Field Debugging of Automotive Microcontrollers for Highest System Availability, in: Proceedings of the 2nd ACM International Workshop on Future Debugging Techniques, DEBT 2024. Association for Computing Machinery, New York, NY, USA, pp. 2–8.. <https://doi.org/10.1145/3678720.3685314>
- Smith, J.G., Hurewitz, T.M., 1958. Design of the RCA 501 System, in: *Papers and Discussions Presented at the December 3-5, 1958, Eastern Joint Computer Conference: Modern Computers: Objectives, Designs, Applications*, AIEE-ACM-IRE '58 (Eastern). Association for Computing

- Machinery, New York, NY, USA, pp. 160–164.. <https://doi.org/10.1145/1458043.1458077>
- Spinellis, D., 2018. Modern Debugging: The Art of Finding a Needle in a Haystack. *Commun. ACM* 61, 124–134.. <https://doi.org/10.1145/3186278>
- Stallman, R., Pesch, R., Shebs, S., others, 1988. Debugging with GDB. Free Software Foundation 675.
- Steegen, S., Tuerlinckx, F., Gelman, A., Vanpaemel, W., 2016. Increasing Transparency Through a Multiverse Analysis. *Perspectives on Psychological Science* 11, 702–712.. <https://doi.org/10.1177/1745691616658637>
- Steinert, B., Cassou, D., Hirschfeld, R., 2012. CoExist: Overcoming Aversion to Change. *SIGPLAN Not.* 48, 107–118.. <https://doi.org/10.1145/2480360.2384591>
- Steinert, B., Perscheid, M., Beck, M., Lincke, J., Hirschfeld, R., 2009. Debugging into Examples, in: Núñez, M., Baker, P., Merayo, M.G. (Eds.), *Testing of Software and Communication Systems*. Springer, Berlin, Heidelberg, pp. 235–240.. https://doi.org/10.1007/978-3-642-05031-2_18
- Stiévenart, Q., Binkley, D., De Roover, C., 2023. Dynamic Slicing of WebAssembly Binaries: 39th IEEE International Conference on Software Maintenance and Evolution. *Proceedings of the 39th IEEE International Conference on Software Maintenance and Evolution (ICSME 2023)* 84–96.. <https://doi.org/10.1109/ICSME58846.2023.00020>
- Stiévenart, Q., Binkley, D.W., De Roover, C., 2022. Static Stack-Preserving Intra-Procedural Slicing of Webassembly Binaries, in: *Proceedings of the 44th International Conference on Software Engineering, ICSE '22*. Association for Computing Machinery, New York, NY, USA, pp. 2031–2042.. <https://doi.org/10.1145/3510003.3510070>
- Strijbol, N., De Proft, R., Goethals, K., Mesuere, B., Dawyndt, P., Scholliers, C., 2024. Blink: An Educational Software Debugger for Scratch. *SoftwareX* 25, 101617.. <https://doi.org/10.1016/j.softx.2023.101617>
- Symeonides, M., Georgiou, Z., Trihinas, D., Pallis, G., Dikaiakos, M., 2020. Fogify: A Fog Computing Emulation Framework, in: *Proceedings - 2020 IEEE/ACM Symposium on Edge Computing, SEC 2020*. pp. 42–54.. <https://doi.org/10.1109/SEC50012.2020.00011>
- Söderby, K., De Feo, U., 2024. Debugging with the Arduino IDE 2.0.
- Tan, S.-L., Anh, T.N.B., 2009. Real-Time Operating System (RTOS) for Small (16-Bit) Microcontroller, in: *2009 IEEE 13th International Symposium*

Bibliography

- on Consumer Electronics. pp. 1007–1011.. <https://doi.org/10.1109/ISCE.2009.5156833>
- Terry, D., Demers, A., Petersen, K., Spreitzer, M., Theimer, M., Welch, B., 1994. Session Guarantees for Weakly Consistent Replicated Data, in: Proceedings of 3rd International Conference on Parallel and Distributed Information Systems. pp. 140–149.. <https://doi.org/10.1109/PDIS.1994.331722>
- Tesone, P., Polito, G., Bouraqadi, N., Ducasse, S., Fabresse, L., 2018. Dynamic Software Update from Development to Production.. The Journal of Object Technology 17, 1.. <https://doi.org/10.5381/jot.2018.17.1.a2>
- Tollervey, N.H., 2022. Code with Mu. a Simple Python Editor for Beginner Programmers.
- Torres Lopez, C., Boix, E.G., Scholliers, C., Marr, S., Mössenböck, H., 2017. A Principled Approach towards Debugging Communicating Event-Loops, in: Proceedings of the 7th ACM SIGPLAN International Workshop on Programming Based on Actors, Agents, And Decentralized Control, AGERE 2017. Association for Computing Machinery, New York, NY, USA, pp. 41–49.. <https://doi.org/10.1145/3141834.3141839>
- Torres Lopez, C., Gurdeep Singh, R., Marr, S., Gonzalez Boix, E., Scholliers, C., 2019. Multiverse Debugging: Non-Deterministic Debugging for Non-Deterministic Programs (Brave New Idea Paper), in: DROPS-IDN/v2/document/10.4230/LIPIcs.ECOOP.2019.27. Schloss Dagstuhl – Leibniz-Zentrum für Informatik.. <https://doi.org/10.4230/LIPIcs.ECOOP.2019.27>
- Ubayashi, N., Kamei, Y., Sato, R., 2019. When and Why Do Software Developers Face Uncertainty?, in: 2019 IEEE 19th International Conference on Software Quality, Reliability and Security (QRS). pp. 288–299.. <https://doi.org/10.1109/QRS.2019.00045>
- Valmari, A., 1998. The State Explosion Problem. Lectures on Petri Nets I: Basic Models: Advances in Petri Nets, Lecture Notes in Computer Science.. https://doi.org/10.1007/3-540-65306-6_21
- van der Veen, V., dutt-Sharma, N., Cavallaro, L., Bos, H., 2012. Memory Errors: The Past, the Present, and the Future, in: Balzarotti, D., Stolfo, S.J., Cova, M. (Eds.), Research in Attacks, Intrusions, And Defenses. Springer, Berlin, Heidelberg, pp. 86–106.. https://doi.org/10.1007/978-3-642-33338-5_5
- VanderVoord, M., Karlesky, M., Williams, G., 2015. UNITY. Unit Testing for C (Especially Embedded Software).

- Vandewoude, Y., Ebraert, P., Berbers, Y., D'Hondt, T., 2007. Tranquility: A Low Disruptive Alternative to Quiescence for Ensuring Safe Dynamic Updates. *IEEE Transactions on Software Engineering* 33, 856–868.. <https://doi.org/10.1109/TSE.2007.70733>
- VanSickle, T., 2001. Programming Microcontrollers in C. Newnes.
- Vishwakarma, G., Lee, W., 2018. Exploiting JTAG and Its Mitigation in IOT: A Survey. *Future Internet* 10, 121.. <https://doi.org/10.3390/fi10120121>
- Waldo, J., Wyant, G., Wollrath, A., Kendall, S., 1997. A Note on Distributed Computing, in: Goos, G., Hartmanis, J., Leeuwen, J., Vitek, J., Tschudin, C. (Eds.), *Mobile Object Systems Towards the Programmable Internet*. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 49–64.. https://doi.org/10.1007/3-540-62852-5_6
- Wasmer, Inc., 2022. Wasmer.
- WebAssembly Community Group, 2022. WebAssembly Proposals.
- WebAssembly/Component-Model, 2025.
- Weiser, M., 1981. Program Slicing, in: *Proceedings of the 5th International Conference on Software Engineering, ICSE '81*. IEEE Press, San Diego, California, USA, pp. 439–449.
- Weiss, A., Gautham, S., Jayakumar, A.V., Elks, C.R., Kuhn, D.R., Kacker, R.N., Preusser, T.B., 2021. Understanding and Fixing Complex Faults in Embedded Cyberphysical Systems. *Computer* 54, 49–60.. <https://doi.org/10.1109/MC.2020.3029975>
- Weiss, G., 1975. Time-Reversibility of Linear Stochastic Processes. *Journal of Applied Probability* 12, 831–836.. <https://doi.org/10.2307/3212735>
- Whitington, J., 2024. Debugging Functional Programs by Interpretation.. <https://doi.org/10.48550/arXiv.2411.00637>
- Wieme, J., Baert, M., Hoebeke, J., 2024. Distributed Automated Testing Framework for Bluetooth Mesh Applications, in: *NOMS 2024-2024 IEEE Network Operations and Management Symposium*. pp. 1–5.. <https://doi.org/10.1109/NOMS59830.2024.10575328>
- Wilkes, M., 1979. The Birth and Growth of the Digital Computer.
- Wilkin, G.A., 2025. "Debugging: From Art to Science" A Case Study on a Debugging Course and Its Impact on Student Performance and Confidence, in: *Proceedings of the 56th ACM Technical Symposium on Computer Science Education V. 1*, SIGCSETS 2025. Association for Computing

Bibliography

- Machinery, New York, NY, USA, pp. 1225–1231.. <https://doi.org/10.1145/3641554.3701893>
- Williams, G., 2014. Espruino.
- Wills, M., 2022. The Bug in the Computer Bug Story.
- Xie, H., 2017. Principles, Patterns, and Techniques for Designing and Implementing Practical Fluent Interfaces in Java, in: Proceedings Companion of the 2017 ACM SIGPLAN International Conference on Systems, Programming, Languages, And Applications: Software for Humanity, SPLASH Companion 2017. Association for Computing Machinery, New York, NY, USA, pp. 45–47.. <https://doi.org/10.1145/3135932.3135948>
- Xu, B., Qian, J., Zhang, X., Wu, Z., Chen, L., 2005. A Brief Survey of Program Slicing. *SIGSOFT Softw. Eng. Notes* 30, 1–36.. <https://doi.org/10.1145/1050849.1050865>
- Yao, Y., Wang, Y., 2005. A Framework for Testing Distributed Software Components, in: Canadian Conference on Electrical and Computer Engineering, pp. 1566–1569.. <https://doi.org/10.1109/CCECE.2005.1557280>
- Yigitler, H., Badihi, B., Jäntti, R., 2020. Overview of Time Synchronization for IoT Deployments: Clock Discipline Algorithms and Protocols. *Sensors* 20, 5928.. <https://doi.org/10.3390/s20205928>
- Yokoyama, T., Axelsen, H.B., Glück, R., 2012. Towards a Reversible Functional Language, in: De Vos, A., Wille, R. (Eds.), *Reversible Computation*. Springer, Berlin, Heidelberg, pp. 14–29.. https://doi.org/10.1007/978-3-642-29517-1_2
- Yokoyama, T., Axelsen, H.B., Glück, R., 2008. Principles of a Reversible Programming Language, in: Proceedings of the 5th Conference on Computing Frontiers, CF '08. Association for Computing Machinery, New York, NY, USA, pp. 43–54.. <https://doi.org/10.1145/1366230.1366239>
- Yukihiro, M., others, 2023. Mruby. Mruby Is the Lightweight Implementation of the Ruby Language Complying with Part of the ISO Standard. Mruby Can Be Linked and Embedded within Your Application.
- Yvon, S., Feeley, M., 2021. A Small Scheme VM, Compiler, and REPL in 4k, in: Proceedings of the 13th ACM SIGPLAN International Workshop on Virtual Machines and Intermediate Languages, VMIL 2021. Association for Computing Machinery, New York, NY, USA, pp. 14–24.. <https://doi.org/10.1145/3486606.3486783>
- Zelkowitz, M.V., 1973. Reversible Execution. *Commun. ACM* 16, 566.. <https://doi.org/10.1145/362342.362360>

- Zeller, A., 2005. Why Programs Fail: A Guide to Systematic Debugging. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA.
- Zerynth s.r.l., 2021. Zerynth Technical Reference v3.0.3.
- Zhu, M.-Y., Wang, C.-W., 1992. Program Derivation in PowerEpsilon, in: 1992 Proceedings. The Sixteenth Annual International Computer Software and Applications Conference. IEEE Computer Society, pp. 206207208209210211–206207208209210211.. <https://doi.org/10.1109/CMP SAC.1992.217567>
- Zhu, M.-Y., 2001. Formal Specifications of Debuggers. SIGPLAN Not. 36, 54–63.. <https://doi.org/10.1145/609769.609778>
- Zhu, M.-Y., Wang, \.C., 1991. A Higher-Order Lambda Calculus: PowerEpsilon.
- Zolfaghari, B., Parizi, R.M., Srivastava, G., Hailemariam, Y., 2021. Root Causing, Detecting, and Fixing Flaky Tests: State of the Art and Future Roadmap. Software: Practice and Experience 51, 851–867.. <https://doi.org/10.1002/spe.2929>

A. Simply typed lambda calculus extensions

The rules for simply typed lambda calculus taken from the definitive work, *Types and Programming Languages* from Benjamin C. Pierce.

<i>New syntactic forms</i>	<i>New evaluation rules</i>	$t \longrightarrow t'$
$t ::=$ (terms)		
...		
<i>true</i>	<i>constant true</i>	$\text{if true then } t_1 \text{ else } t_2 \longrightarrow t_1$
<i>false</i>	<i>constant false</i>	$\text{if false then } t_1 \text{ else } t_2 \longrightarrow t_2$
<i>if t then t else t</i>	<i>conditional</i>	$t_1 \longrightarrow t'_1$
<i>0</i>	<i>constant zero</i>	$\frac{\text{if } t_1 \text{ then } t_2 \text{ else } t_3}{\longrightarrow \text{if } t'_1 \text{ then } t_2 \text{ else } t_3}$
<i>succ t</i>	<i>succ</i>	
<i>iszero t</i>	<i>iszero</i>	
$v ::=$ (values)	<i>New typing rules</i>	$\boxed{\Gamma \vdash t : T}$
...		
<i>true</i>	<i>true value</i>	$\boxed{\Gamma \vdash \text{true} : \text{Bool}}$
<i>false</i>	<i>false value</i>	$\boxed{\Gamma \vdash \text{false} : \text{Bool}}$
<i>n</i>	<i>numerical value</i>	
$n ::=$ (numeric values)		
<i>0</i>		$\frac{\Gamma \vdash t_1 : \text{Bool} \quad \Gamma \vdash t_2 : T}{\Gamma \vdash \text{if } t_1 \text{ then } t_2 \text{ else } t_3 : T}$
<i>succ n</i>	<i>constant true</i>	
$T ::=$ (types)		
...		
<i>Bool</i>	<i>booleans</i>	$\boxed{\Gamma \vdash 0 : \text{Nat}}$
<i>Nat</i>	<i>natural numbers</i>	
		$\frac{\Gamma \vdash t_1 : \text{Nat}}{\Gamma \vdash \text{succ } t_1 : \text{Nat}}$
		$\frac{\Gamma \vdash t_1 : \text{Nat}}{\Gamma \vdash \text{pred } t_1 : \text{Nat}}$
		$\frac{\Gamma \vdash t_1 : \text{Nat}}{\Gamma \vdash \text{iszero } t_1 : \text{Bool}}$

Figure A-1. Natural numbers and booleans for λ^\rightarrow . The syntax, evaluation, and typing rules for the natural numbers and booleans (Pierce, 2002).

<i>New syntactic forms</i>		
$t ::= \dots$	<i>(terms)</i>	$\frac{t_1 \rightarrow t'_1}{\text{let } x = t_1 \text{ in } t_2 \rightarrow \text{let } x = t'_1 \text{ in } t_2} \quad (\text{Let})$
$\text{let } x = t \text{ in } t$	<i>let binding</i>	
<i>New evaluation rules</i>	$[t \longrightarrow t'] \quad (\text{LetV})$	<i>Typing</i> $[\Gamma \vdash t : T]$
$\text{let } x = v_1 \text{ in } t_2 \rightarrow [x \mapsto v_1]t_2$		$\frac{\begin{array}{c} \Gamma \vdash t_1 : T_1 \\ \Gamma, x : T_1 \vdash t_2 : T_2 \end{array}}{\Gamma \vdash \text{let } x = t_1 \text{ in } t_2 : T_2} \quad (\text{T-Let})$

Figure A-2. Let bindings for λ^\rightarrow . The syntax, evaluation, and typing rules for let bindings (Pierce, 2002).

B. Full syntax and evaluation rules for the debugger

In this appendix we provide the unabbreviated semantic rules for the debuggers from Chapter 2.

B.1 The conventional debugger

Syntactic forms

$d ::=$	$c \mid s$	<i>(global debugger)</i>	$m_c ::=$	<i>(debug commands)</i>
$s ::=$	$\langle m_c, m_s, n, e, b ; t \rangle$	<i>(server)</i>	\emptyset step inspect	<i>nothing</i> <i>single step</i> <i>inspection</i>
$c ::=$	m_c, m_s	<i>(client)</i>	play	<i>unpause</i>
$m_s ::=$	\emptyset snap t ack m_c hit n	<i>(server messages)</i>	pause $bp^+(n)$ $bp^-(n)$ breakpoint hit	<i>pause</i> <i>add breakpoint</i> <i>remove breakpoint</i>
$e ::=$			paused play	<i>(execution state)</i> <i>paused state</i> <i>unpaused state</i>
$b ::=$				<i>(breakpoints)</i>
			\emptyset n, b	<i>empty</i> <i>list of numerics</i>

Numericals from λ^+

$n ::=$	0	<i>(numeric values)</i>
	$succ\ n$	<i>constant zero</i> <i>succ</i>

New initial configuration

$$d_{\text{start}} = \langle \emptyset, \emptyset \rangle \mid \langle \emptyset, \emptyset, 0, \text{paused}, \emptyset ; t_{\text{start}} \rangle$$

Figure B-3. Syntax rules of the conventional live debugger $\lambda_{\mathbb{D}}$. The complete set of syntax rules for *pause*, *play*, and *breakpoints* for the $\lambda_{\mathbb{D}}^*$ debugger semantics. Changes to the minimal rules in Figure 2-2 are highlighted.

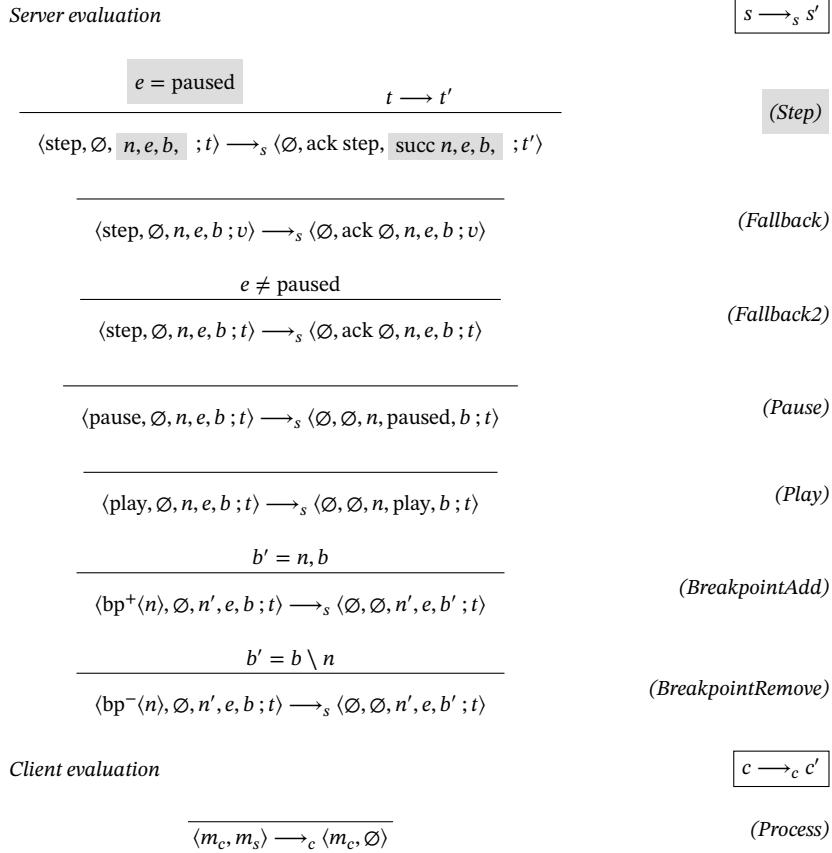


Figure B-4. Server and client evaluation of conventional live debugger operations for $\lambda_{\overrightarrow{\mathbb{D}}}$. Changes to the minimal rules in Figure 2-2 are highlighted.

$$\begin{array}{c}
 \text{Global evaluation} \qquad \boxed{d \longrightarrow_{\mathbb{D}} d'}
 \\[10pt]
 \hline
 \frac{}{\langle m_c, \emptyset \rangle \mid \langle \emptyset, \emptyset, n, e, b ; t \rangle} \qquad \qquad \qquad \text{(Input)}
 \\[10pt]
 \frac{}{\langle m_c, \emptyset \rangle \mid \langle \emptyset, m_s, n, e, b ; t \rangle} \qquad \qquad \qquad \text{(Output)}
 \\[10pt]
 \frac{c \xrightarrow{c \longrightarrow_c c'} \qquad \qquad \qquad \text{(Client)}}{c \mid s \longrightarrow_{\mathbb{D}} c \mid s}
 \\[10pt]
 \frac{s \xrightarrow{s \longrightarrow_s s'} \qquad \qquad \qquad \text{(Server)}}{c \mid s \longrightarrow_{\mathbb{D}} c \mid s}
 \\[10pt]
 \frac{e = \text{play} \qquad \qquad t \longrightarrow t' \qquad \qquad n \notin b}{\langle \emptyset, \emptyset \rangle \mid \langle \emptyset, \emptyset, n, e, b ; t \rangle \longrightarrow_{\mathbb{D}} \langle \emptyset, \emptyset \rangle \mid \langle \emptyset, \emptyset, \text{succ } n, e, b ; t' \rangle} \qquad \qquad \text{(Run)}
 \\[10pt]
 \hline
 \frac{n \in b}{\langle m_c, \emptyset \rangle \mid \langle \emptyset, \emptyset, n, \text{play}, b ; t \rangle \longrightarrow_{\mathbb{D}} \langle m_c, \emptyset \rangle \mid \langle \emptyset, \text{hit } n, n, \text{paused}, b ; t \rangle} \qquad \qquad \text{(BreakpointHit)}
 \end{array}$$

Figure B-5. Global evaluation rules of conventional live debugger operations for $\lambda_{\mathbb{D}}$. Changes to the minimal rules in Figure 2-2 are highlighted.

B.2 The reversible debugger

Syntactic forms

$d ::=$	(global debugger)	$m_c ::=$	(debug commands)
$c \mid s$			
$s ::=$	(server)	\emptyset	nothing
$\langle m_c, m_s, [n], e, b, [z] ; t \rangle$		step	single step
$c ::=$	(client)	inspect	inspection
m_c, m_s		play	unpause
$m_s ::=$	(server messages)	pause	pause
\emptyset	nothing	bp ⁺ (n)	add breakpoint
snap t	term	bp ⁻ (n)	remove breakpoint
ack m_c	acknowledgement		
hit n	breakpoint hit	step [←]	backwards step
$z ::=$	(snapshots)	$e ::=$	(execution state)
$(0, t)$	start snapshot	paused	paused state
$(n, t), z$	list of snapshots	play	unpaused state
<hr/>		$b ::=$	(breakpoints)
		\emptyset	empty
		n, b	list of numerics

Numericals from λ^\rightarrow

New initial configuration

$n ::=$	(numeric values)	$d_{\text{start}} =$
0	constant zero	$\langle \emptyset, \emptyset \rangle \mid \langle \emptyset, \emptyset, 0, \text{paused}, \emptyset, (0, t) ; t_{\text{start}} \rangle$
succ n	succ	

Figure B-6. Syntax rules of the reversible debugger $\lambda_{\mathbb{D}}^{\leftarrow}$. The reversible specific parts are highlighted.

Server evaluation

	$s \longrightarrow_s s'$
$e = \text{paused}$ $t \longrightarrow t'$	$\langle \text{step}, \emptyset, n, e, b, z ; t \rangle \longrightarrow_s \langle \emptyset, \text{ack step succ } n, e, b, z ; t' \rangle$
	$\langle \text{step}, \emptyset, n, e, b, z ; v \rangle \longrightarrow_s \langle \emptyset, \text{ack } \emptyset, n, e, b, z ; v \rangle$
$e \neq \text{paused}$	$\langle \text{step}, \emptyset, n, e, b, z ; t \rangle \longrightarrow_s \langle \emptyset, \text{ack } \emptyset, n, e, b, z ; t \rangle$
	$\langle \text{pause}, \emptyset, n, e, b, z ; t \rangle \longrightarrow_s \langle \emptyset, \emptyset, n, \text{paused}, b, z ; t \rangle$
	$\langle \text{play}, \emptyset, n, e, b, z ; t \rangle \longrightarrow_s \langle \emptyset, \emptyset, n, \text{play}, b, z ; t \rangle$
$b' = n, b$	$\langle \text{bp}^+(\langle n \rangle), \emptyset, n', e, b, z ; t \rangle \longrightarrow_s \langle \emptyset, \emptyset, n', e, b', z ; t \rangle$
$b' = b \setminus n$	$\langle \text{bp}^-(\langle n \rangle), \emptyset, n', e, b, z ; t \rangle \longrightarrow_s \langle \emptyset, \emptyset, n', e, b', z ; t \rangle$
$z = (0, t')$	$e = \text{paused}$ $t' \longrightarrow^n t''$
	$\langle \text{step}^\leftarrow, \emptyset, \text{succ } n, e, b, z ; t \rangle \longrightarrow_s \langle \emptyset, \text{ack step}^\leftarrow, n, e, b, z ; t'' \rangle$
$n \neq n'$ $z = ((n', t'), z')$	$e = \text{paused}$ $t' \longrightarrow^{n-n'} t''$
	$\langle \text{step}^\leftarrow, \emptyset, \text{succ } n, e, b, z ; t \rangle \longrightarrow_s \langle \text{ack step}^\leftarrow, \emptyset, n, e, b, z ; t'' \rangle$
$z = ((n, t'), z')$	$e = \text{paused}$
	$\langle \text{step}^\leftarrow, \emptyset, \text{succ } n, e, b, z ; t \rangle \longrightarrow_s \langle \emptyset, \text{ack step}^\leftarrow, n, e, b, z' ; t' \rangle$
$e \neq \text{paused}$	$\langle \text{step}^\leftarrow, \emptyset, n, e, b, z ; t \rangle \longrightarrow_s \langle \emptyset, \text{ack } \emptyset, n, e, b, z ; t \rangle$
	$z = (0, t)$
	$\langle \text{step}^\leftarrow, \emptyset, 0, e, b, z ; t \rangle \longrightarrow_s \langle \emptyset, \text{ack } \emptyset, 0, e, b, z ; t \rangle$

Figure B-7. Server evaluation of the reversible debugger operations for $\lambda_{\mathbb{D}}^\leftarrow$. The reversible specific parts are highlighted.

<i>Client evaluation</i>	$c \xrightarrow{c} c'$
	$\overline{\langle m_c, m_s \rangle \longrightarrow_c \langle m_c, \emptyset \rangle}$ <i>(Process)</i>
<i>Global evaluation</i>	$d \xrightarrow{\mathbb{D}} d'$
	$\overline{\langle m_c, \emptyset \rangle \mid \langle \emptyset, \emptyset ; t \rangle} \longrightarrow_{\mathbb{D}} \langle \emptyset, \emptyset \rangle \mid \langle m_c, \emptyset ; t \rangle$ <i>(Input)</i>
	$\overline{\langle m_c, \emptyset \rangle \mid \langle \emptyset, m_s ; t \rangle} \longrightarrow_{\mathbb{D}} \langle m_c, m_s \rangle \mid \langle \emptyset, \emptyset ; t \rangle$ <i>(Output)</i>
	$\frac{c \xrightarrow{c} c'}{c \mid s \xrightarrow{\mathbb{D}} c \mid s}$ <i>(Client)</i>
	$\frac{s \xrightarrow{s} s'}{c \mid s \xrightarrow{\mathbb{D}} c \mid s}$ <i>(Server)</i>
$e = \text{play} \quad t \longrightarrow t' \quad z' = ((\text{succ } n, t'), z) \quad n \notin b$ $(\text{succ } n) \% \theta = 0$	$\overline{\langle \emptyset, \emptyset \rangle \mid \langle \emptyset, \emptyset, n, e, b, z ; t \rangle \longrightarrow_{\mathbb{D}} \langle \emptyset, \emptyset \rangle \mid \langle \emptyset, \emptyset, \text{succ } n, e, b, z' ; t' \rangle}$ <i>(Run1)</i>
$e = \text{play} \quad t \longrightarrow t' \quad n \notin b \quad (\text{succ } n) \% \theta \neq 0$	$\overline{\langle \emptyset, \emptyset \rangle \mid \langle \emptyset, \emptyset, n, e, b, z ; t \rangle \longrightarrow_{\mathbb{D}} \langle \emptyset, \emptyset \rangle \mid \langle \emptyset, \emptyset, \text{succ } n, e, b, z ; t' \rangle}$ <i>(Run2)</i>
$n \in b$	$\overline{\langle m_c, \emptyset \rangle \mid \langle \emptyset, \emptyset, n, \text{play}, b, z ; t \rangle \longrightarrow_{\mathbb{D}} \langle m_c, \emptyset \rangle \mid \langle \emptyset, \text{hit } n, n, \text{paused}, b, z ; t \rangle}$ <i>(BreakpointHit)</i>

Figure B-8. Client and global evaluation rules of the reversible debugger operations ($\lambda_{\mathbb{D}}$). The reversible specific parts are highlighted.

B.3 The intercession debugger

Syntactic forms

$d ::=$	(global debugger)	$m_c ::=$	(debug commands)
$c \mid s$			
$s ::=$	(server)	\emptyset	nothing
$\langle m_c, m_s, n, e, b, z ; t \rangle$		step	single step
$c ::=$	(client)	inspect	inspection
m_c, m_s		play	unpause
$m_s ::=$	(server messages)	pause	pause
\emptyset	nothing	bp ⁺ $\langle n \rangle$	add breakpoint
snap t	term	bp ⁻ $\langle n \rangle$	remove breakpoint
ack m_c	acknowledgement	step [←]	backwards step
hit n	breakpoint hit	subst $t_1 t_2$	substitute
$z ::=$	(snapshots)	$e ::=$	(execution state)
$(0, t)$	start snapshot	paused	paused state
$(n, t), z$	list of snapshots	play	unpaused state
		$b ::=$	(breakpoints)
		\emptyset	empty
		n, b	list of numerics

Numericals from λ^\rightarrow	New initial configuration
$n ::=$	(numeric values)
0	constant zero
succ n	succ
	$d_{\text{start}} =$
	$\langle \emptyset, \emptyset \rangle \mid \langle \emptyset, \emptyset, 0, \text{paused}, \emptyset, (0, t) ; t_{\text{start}} \rangle$

Figure B-9. Syntax rules of the intercession debugger $\lambda_{\mathbb{D}}^{\sharp}$. The intercession specific parts are highlighted.

Server evaluation

$$s \xrightarrow{s'} s'$$

$e = \text{paused}$	$t \longrightarrow t'$	$(Step)$
$\langle \text{step}, \emptyset, n, e, b, z ; t \rangle \longrightarrow_s \langle \emptyset, \text{ack step}, \text{succ } n, e, b, z ; t' \rangle$		
<hr/>		
$\langle \text{step}, \emptyset, n, e, b, z ; v \rangle \longrightarrow_s \langle \emptyset, \text{ack } \emptyset, n, e, b, z ; v \rangle$		$(Fallback)$
<hr/>		
$e \neq \text{paused}$		
<hr/>		
$\langle \text{step}, \emptyset, n, e, b, z ; t \rangle \longrightarrow_s \langle \emptyset, \text{ack } \emptyset, n, e, b, z, ; t \rangle$		$(Fallback2)$
<hr/>		
$\langle \text{pause}, \emptyset, n, e, b, z ; t \rangle \longrightarrow_s \langle \emptyset, \emptyset, n, \text{paused}, b, z ; t \rangle$		$(Pause)$
<hr/>		
$\langle \text{play}, \emptyset, n, e, b, z ; t \rangle \longrightarrow_s \langle \emptyset, \emptyset, n, \text{play}, b, z ; t \rangle$		$(Play)$
<hr/>		
$b' = n, b$		
<hr/>		
$\langle \text{bp}^+(\langle n \rangle), \emptyset, n', e, b, z ; t \rangle \longrightarrow_s \langle \emptyset, \emptyset, n', e, b', z ; t \rangle$		$(BreakpointAdd)$
<hr/>		
$b' = b \setminus n$		
<hr/>		
$\langle \text{bp}^-(\langle n \rangle), \emptyset, n', e, b, z ; t \rangle \longrightarrow_s \langle \emptyset, \emptyset, n', e, b', z ; t \rangle$		$(BreakpointRemove)$
<hr/>		
$z = (0, t')$	$e = \text{paused}$	$t' \longrightarrow^n t''$
<hr/>		
$\langle \text{step}^\leftarrow, \emptyset, \text{succ } n, e, b, z ; t \rangle \longrightarrow_s \langle \emptyset, \text{ack step}^\leftarrow, n, e, b, z ; t'' \rangle$		$(BackwardStep0)$
<hr/>		
$n \neq n'$	$z = ((n', t'), z')$	$e = \text{paused}$
		$t' \longrightarrow^{n-n'} t''$
<hr/>		
$\langle \text{step}^\leftarrow, \emptyset, \text{succ } n, e, b, z ; t \rangle \longrightarrow_s \langle \text{ack step}^\leftarrow, \emptyset, n, e, b, z ; t'' \rangle$		$(BackwardStep1)$
<hr/>		
$z = ((n, t'), z')$	$e = \text{paused}$	
<hr/>		
$\langle \text{step}^\leftarrow, \emptyset, \text{succ } n, e, b, z ; t \rangle \longrightarrow_s \langle \emptyset, \text{ack step}^\leftarrow, n, e, b, z' ; t' \rangle$		$(BackwardStep2)$
<hr/>		
$e \neq \text{paused}$		
<hr/>		
$\langle \text{step}^\leftarrow, \emptyset, n, e, b, z ; t \rangle \longrightarrow_s \langle \emptyset, \text{ack } \emptyset, n, e, b, z ; t \rangle$		$(BackwardFallback1)$
<hr/>		

,

Figure B-10. Server evaluation of the intercession debugger operations for $\lambda_{\mathbb{D}}^{\sharp}$. The intercession specific parts are highlighted.

Appendix B.3. Full syntax and evaluation rules for the debugger

$\frac{z = (0, t)}{\langle \text{step}^+, \emptyset, 0, e, b, z ; t \rangle \longrightarrow_s \langle \emptyset, \text{ack } \emptyset, 0, e, b, z ; t \rangle}$	<i>(BackwardFallback2)</i>
$\frac{\Gamma \vdash t_2 : T' \quad \Gamma, t_1 : T' \vdash t : T}{\langle \text{subst } t_1 t_2, \emptyset, n, e, b, z ; t \rangle \longrightarrow_s \langle \emptyset, \text{ack subst } t_1 t_2, n, e, b, z ; [t_1 \mapsto t_2] t \rangle}$	<i>(Subst)</i>
<i>Client evaluation</i>	$c \longrightarrow_c c'$
<i>Global evaluation</i>	$d \longrightarrow_{\mathbb{D}} d'$
$\frac{\langle m_c, \emptyset \rangle \mid \langle \emptyset, \emptyset ; t \rangle}{\longrightarrow_{\mathbb{D}} \langle \emptyset, \emptyset \rangle \mid \langle m_c, \emptyset ; t \rangle}$	<i>(Input)</i>
$\frac{\langle m_c, \emptyset \rangle \mid \langle \emptyset, m_s ; t \rangle}{\longrightarrow_{\mathbb{D}} \langle m_c, m_s \rangle \mid \langle \emptyset, \emptyset ; t \rangle}$	<i>(Output)</i>
$\frac{c \longrightarrow_c c'}{c \mid s \longrightarrow_{\mathbb{D}} c \mid s}$ $\frac{s \longrightarrow_s s'}{c \mid s \longrightarrow_{\mathbb{D}} c \mid s}$	<i>(Client)</i>
$\frac{e = \text{play} \quad t \longrightarrow t' \quad z' = ((\text{succ } n, t'), z) \quad n \notin b \quad (\text{succ } n) \% \theta = 0}{\langle \emptyset, \emptyset \rangle \mid \langle \emptyset, \emptyset, n, e, b, z ; t \rangle \longrightarrow_{\mathbb{D}} \langle \emptyset, \emptyset \rangle \mid \langle \emptyset, \emptyset, \text{succ } n, e, b, z' ; t \rangle}$	<i>(Run1)</i>
$\frac{e = \text{play} \quad t \longrightarrow t' \quad n \notin b \quad (\text{succ } n) \% \theta \neq 0}{\langle \emptyset, \emptyset \rangle \mid \langle \emptyset, \emptyset, n, e, b, z ; t \rangle \longrightarrow_{\mathbb{D}} \langle \emptyset, \emptyset \rangle \mid \langle \emptyset, \emptyset, \text{succ } n, e, b, z ; t' \rangle}$	<i>(Run2)</i>
$\frac{n \in b}{\langle m_c, \emptyset \rangle \mid \langle \emptyset, \emptyset, n, \text{play}, b, z ; t \rangle \longrightarrow_{\mathbb{D}} \langle m_c, \emptyset \rangle \mid \langle \emptyset, \text{hit } n, n, \text{paused}, b, z ; t \rangle}$	<i>(BreakpointHit)</i>

Figure B-11. Server (cont.), client and global evaluation rules of the intercession debugger operations ($\lambda_{\mathbb{D}}^{\sharp}$). The intercession specific parts are highlighted.

C. WebAssembly Specification Summary

In this appendix, we will discuss the elements of WebAssembly needed to understand the formalization of our extensions. A full and detailed account of all WebAssembly's formal semantics can be found in the excellent paper of Haas et al. (2017).

(value types)	$t ::= \text{i32} \mid \text{i64} \mid \text{f32} \mid \text{f64}$
(packed types)	$tp ::= \text{i8} \mid \text{i16} \mid \text{i32}$
(function types)	$tf ::= t^* \rightarrow t^*$
(global types)	$tg ::= \text{mut}^? t$
(instructions)	$e ::= \text{unreachable} \mid \text{nop} \mid \text{drop} \mid \text{select} \mid \text{block } tf \ e^* \ \text{end} \mid$ $\text{loop } tf \ e^* \ \text{end} \mid \text{if } tf \ e^* \ \text{else } e^* \ \text{end} \mid \text{br } i \mid \text{br_if } i \mid$ $\text{br_table } i^+ \mid \text{return} \mid \text{call } i \mid \text{call_indirect } tf \mid$ $\text{local.get } i \mid \text{local.set } i \mid \text{local.tee } i \mid \text{global.get } i \mid$ $\text{global.set } i \mid t.\text{load } (tp_{\text{sx}})^? \ a \ o \mid t.\text{store } tp^? \ a \ o \mid$ $\text{current_memory} \mid \text{grow_memory} \mid t.\text{const } c \mid$ $t.\text{unop}_t \mid t.\text{binop}_t \mid t.\text{testop}_t \mid t.\text{relop}_t \mid t.\text{cvtop } t_{\text{sx}}^?$
(functions)	$f ::= ex^* \ \text{func } tf \ \text{local } t^* e^* \mid ex^* \ \text{func } tf \ \text{im}$
(globals)	$glob ::= ex^* \ \text{global } tg \ e^* \mid ex^* \ \text{global } tg \ \text{im}$
(tables)	$tab ::= ex^* \ \text{table } ni^* \mid ex^* \ \text{table } n \ \text{im}$
(memories)	$mem ::= ex^* \ \text{memory } n \mid ex^* \ \text{memory } n \ \text{im}$
(imports)	$im ::= \text{import } "name" \ "name"$
(exports)	$ex ::= \text{export } "name"$
(modules)	$m ::= \text{module } tf^* \ f^* \ glob^* \ tab^? \ mem^?$

Figure C-12. Core WebAssembly syntax evaluation rules as defined in Haas et al. (2017).

C.1 Modules and Imports

A WebAssembly binary is organized as a *module*, which can only interact with its environment through typed imports and exports. WebAssembly embraces this strict encapsulation to better protect against possible security vulnerabilities associated with running WebAssembly bytecode in the browser. To further strengthen the security of WebAssembly, the language is defined with a strict type system that allows for fast static validation. As the last line of figure Figure C-12 shows, a WebAssembly module contains *function types*, *functions*, *globals*, *tables* and at most one *memory*. All of these definitions, except *function types*, can be imported from other modules as well as exported under one or more names.

The life cycle of a WebAssembly module can be divided into three stages. In the first stage, the WebAssembly code is statically validated by the type system. This is usually done before compilation. After compilation the code can be executed by a WebAssembly runtime, such as WARDuino or a web browser. In the second stage, the runtime turns the module $m = (\text{module}, \text{tf}^*, f^*, \text{glob}^*, \text{tab}^?, \text{mem}^?)$ into a dynamic instance inst . As shown in figure Figure C-14, all instances are kept in the WebAssembly global store s . During instantiation, the runtime must provide definitions for all imports, and it must allocate mutable memory. Finally, after this second stage, the WebAssembly code can be executed.

C.2 Control Flow

WebAssembly differs from traditional instruction sets in the way it prevents control flow hijacking (Burow et al., 2017, Lehmann et al., 2020). The instruction set does not allow arbitrary jumps, but only offers structured control flow. This means that unrestricted jumps do not exist. Instead, branches can only jump to the end of well-nested blocks inside the current function.

WebAssembly features three control constructs, loop, if, and block. These constructs all terminate with an end instruction. The sequence of instructions e^* captured between these instructions form a so-called block. The if can optionally hold two instruction sequences, separated by an extra else opcode. When an if instruction is executed, and the top of the stack is a non-zero number, the first block is executed, otherwise the second block is. Executing a executes the instructions captured in it unconditionally.

A branch instruction (br) specifies a target i . This target must be one of the blocks the br instruction is executed in. If the target is a if or block, executing the branch will skip any instruction between the position of the br and the end of the targeted block. Branching to a loop jumps to the start of that loop. Counter-intuitively, the construct does not loop automatically. Instead, the br instructions allow it to be repeated. Branches may also be conditional. A br_if will only branch if the value on the top of the stack is non-zero. The br_table, takes a list of targets and branches to the n -th target if the number n is on the top of the stack.

br_table jumps to its last target if the index is out of bounds.

C.3 Functions

Modules contain a list of functions (func tf local t^*e^*). All functions have a function type tf of the form $t_1^* \rightarrow t_2^*$. Because WebAssembly is a stack based language, this type describes the action of a function on the stack. The value types t_1^* before the arrow indicate the types of the elements the function

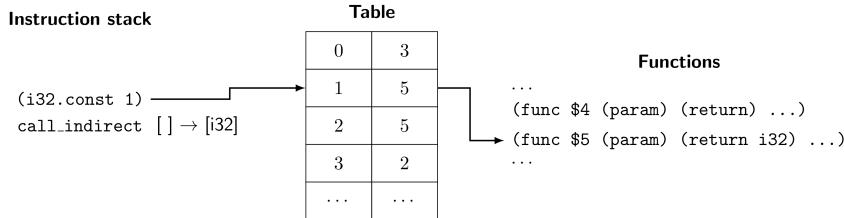


Figure C-13. Indirect function call in WebAssembly via the table section.

expects to be on top of the stack when called. After the arrow, t_2^* indicates the return type. The type $i32 \times i32 \rightarrow f32$ is used for a function that pops two 32-bit integers from the stack and pushes one 32-bit floating point number on the stack. Functions may also have local variables, these are declared as a list of value types after the function type as follows: $\text{local } t^*$. These local variables are zero-initialized. The arguments and the local variables can be read or written via the `local.get` and `local.set` instructions respectively. Both instructions take the index of the argument or local as argument. The body of a function e^* is a sequence of instructions that leaves the stack in a state matching the function's return type.

Although a star is used, WebAssembly functions in Haas et al. (2017) only return a single value.

C.4 Function Calls and Tables

Aside from arbitrary control flow, WebAssembly also lacks function pointers. It does provide an alternative with the instruction. This instruction can use a table to call functions based on an index operand calculated at runtime, similar to the instruction. Figure Figure C-13 illustrates how this works. The instruction takes the value at the top of the stack and uses that to index a table of function references. Each table index corresponds to a function index, which in its turn points to a function. Tables can hold functions of different types, so the instruction takes a statically encoded argument specifying the type of the function it calls. At runtime, this encoded type is checked against the type of the function the index points to. If these do not correspond, the call is aborted, and a trap is thrown.

C.5 WebAssembly Linear Memory

The memory in WebAssembly is referred to as linear memory because it is a large array of bytes. Conceptually, the memory is divided into pages of 64 KiB. The size of memory is specified in terms of these pages, and linear memory can grow any number of pages at a time as long as the runtime can allocate the required space. Allocating additional pages can be done with the `grow_memory` instruction. While the specification leaves the possibility

of multiple memories open, WebAssembly still explicitly supports only one memory. However, a proposal for multiple memories is already in the implementation phase and so can be expected to be added to the standard in due course.

C.6 Execution

The execution of a WebAssembly program is described by a small-step reduction relation \hookrightarrow_i over a configuration triple representing the state of the VM. A configuration contains one global store s , the local values v^* and the active instruction sequence e^* being executed. The rules are of the form $s; v^*; e^* \hookrightarrow_i s'; v'^*; e'^*$. In figure Figure C-14, we present the most relevant small-step reduction rules for WARDuino.

WebAssembly syntax rules

(store)	$s ::= \{inst\ inst^*, tab\ tabinst^*, mem\ meminst^*\}$
(instances)	$inst ::= \{\text{func } cl^*, \text{glob } v^*, \text{tab } i^?, \text{mem } i^?\}$
	$\text{tabinst} ::= cl^*$
	$\text{meminst} ::= b^*$
(closures)	$cl ::= \{inst\ i, code\ f\}$
(values)	$v ::= t.\text{const } c$
(admin. oper.)	$e ::= \dots \mid \text{call } cl \mid \text{label}_n\{e^*\} e^* \text{ end} \mid \text{local}_n\{i; v^*\} e^* \text{ end}$
(local contexts)	$L^0 ::= v^*[_]e^*$
	$L^{[k+1]} ::= \text{label}_n\{e^*\} L^k \text{ end } e^*$

WebAssembly evaluation rules

$$\begin{array}{c}
 \frac{s; v^*; e^* \hookrightarrow_i s'; v'^*; e'^*}{s; v^*, L^{[e^*]} \hookrightarrow_i s'; v'^*; L^{[e'^*]}} \text{STEP-I} \\
 \frac{s; v^*; e^* \hookrightarrow_i s'; v'^*; e'^*}{s; v_0^*; \text{local}_n\{i; v'^*\} e'^* \text{ end} \hookrightarrow_{d,i} s'; v_0^*; \text{local}_n\{i; v^*\} e^* \text{ end}} \text{STEP-LOCAL} \\
 \frac{s; v^*; e^* \hookrightarrow_i s'; v'^*; e'^* \quad s_{\{tab\}}(i, j)_{\{\text{code}\}} = (\text{func } tf \text{ local } t^* e^*)}{s; v_0^*; (\text{i32.const } j) \text{ call_indirect } tf \hookrightarrow_i s'; v_0^*; \text{call } s_{\{tab\}}(i, j)} \text{STEP-INDIRECT} \\
 \frac{s; v^*; e^* \hookrightarrow_i s'; v'^*; e'^* \quad s_{\{tab\}}(i, j)_{\{\text{code}\}} \neq (\text{func } tf \text{ local } t^* e^*)}{s; v_0^*; (\text{i32.const } j) \text{ call_indirect } tf \hookrightarrow_i s'; v_0^*; \text{trap}} \text{STEP-INDIRECT-TRAP}
 \end{array}$$

Figure C-14. WebAssembly meta-rules.

At the top of the figure, we list all the relevant syntax for the rules. The store s consists of a set of module instances, table instances and memory instances. Tables and memories are only referenced by their index, since they can be shared between modules. A module instance consists of closures, global variables, tables and memories. A closure is the instantiated version of a function, and is represented by a tuple of the module instance and a code block. Values consist of constants. To elegantly represent the semantics a number of administrative operators are added to the list of instructions. The most important ones are **local** and **label**. The **local** operator indicates a call frame for function invocation (possibly over module boundaries), while the **label** operator marks the extent of a control construct.

Appendix C.6. WebAssembly Specification Summary

In the lower part of figure Figure C-14, we show some important small-step reduction rules for WebAssembly execution in WARDuino. Aside from the configuration $\{s, v^*, e^*\}$, the small step reduction rules operate on the currently executing instance. That is why the small-step reduction is indexed by the address i of that instance. The first two reduction rules govern the order of evaluation. The STEP-I rule splits a configuration into its context L^k and its focus and takes one step of the \hookrightarrow_i relation. The second rule STEP-LOCAL explains how to evaluate a function that might reside in a different module. Note that this step changes the currently executing module, indicated by the two indices of the small-step relation $\hookrightarrow_{d,i}$. The last two rules are included because they are particularly relevant to our callback handling extension. The first rule, STEP-INDIRECT, transforms a instruction into a standard instruction. The STEP-INDIRECT rule takes a runtime index j , and an immediate function type tf . The index j must correspond to a function of the given type in the table of the current module $s_{tab}(i, j)$. If this is the case, the indirect call is replaced with a call to the function. On the other hand, when no correct function is found, the indirect call is replaced by a as shown by STEP-INDIRECT-TRAP. This means the program will stop executing. When all goes well, the resulting call can be reduced further. We omit any further reduction rules from the WebAssembly standard, because they are not changed or not relevant to the further discussion in this section. The interested reader can find all WebAssembly reduction rules in the original WebAssembly article (Haas et al., 2017).

Now we have all the formal tools required to describe the extensions to WebAssembly implemented in WARDuino. We will discuss each extension in turn in the following sections.

D. Built-in Modules

In this appendix, we give an overview of the WARDuino VM's built-in modules, which provide primitives for controlling peripheral hardware and other essential aspects of IoT applications. The examples are written in WebAssembly's textual format.

This appendix is taken from the WARDuino overview paper (Lauwaerts et al., 2024), and is meant as a quick reference for Chapter 3. However, the exact interfaces of the primitives are subject to changes, and many additional modules have been added since. The most up-to-date overview can be found on the official WARDuino [documentation website](#), which at the time of writing is still primarily maintained by myself.

D.1 Input-Output Pins

A first module exposes the hardware pins of the microcontroller. In a microcontroller each pin is connected through a so-called port. A port controls the properties of a pin, such as its mode. The mode of a pin determines if it can be used for reading or writing, it is important to make sure the mode of the pin is always set correctly.

Arduino abstracts away the division between ports and pins through a simple API. This API allows us to set the pin mode, read the pin or write a value to it. In WARDuino we defined a native implementation of these functions in an IO module. The signatures of the functions in our IO module are listed on the right side of figure Figure D-15. The first function, `pin_mode` returns no values, but takes two `i32` arguments; the first argument identifies the pin and the second the mode, either `input`, `output`, or `input_pullup`. The second function `digital_write` has no return value and takes two arguments. Again, the first argument specifies the pin, and this time the second argument provides the value to be written to the digital pin, either `high` or `low`. Finally, the `digital_read` function takes a digital pin as argument, and returns the value read from the specified pin, either `high` or `low`, as an `i32` value.

32 bit integers

D.2 Pulse Width Modulation and Analog Reads

A pulse width modulator (PWM) allows programmers to send out a square wave to one of the output pins without having to write a busy loop. The duty cycle is the configurable fraction of time the wave is high. PWM is prototypically used to dim an LED, sending it a square wave makes it flash very fast,

Appendix D.2. Built-in Modules

```

1  (module
2  ; type declarations ;
3  (type $int->int->vd (func (param i32)
4  (param i32) (result)))
4  (type $int->vd      (func (param i32)
5  (result)))
5  (type $vd->vd      (func (param)
6  (result)))
6  ; imports ;
7  (import "env" "pin_mode"      (func
8  $pin_mode (type $int->int->vd)))
8  (import "env" "digital_write" (func
9  $dig_write (type $int->int->vd)))
9  (import "env" "delay"        (func
10 $delay (type $int->vd)))
10 ; export $blink as the main entry point
10   of the program ;
11  (export "main" (func $blink))
12  ; blink function ;
13  (func $blink (type $vd->vd)
14    (call $pin_mode (i32.const 16)
14     (i32.const 1)) ; write mode ;
15  (loop $begin
16    (call $dig_write (i32.const 16)
16     (i32.const 0)) ; off ;
17    (call $delay (i32.const 5000)) ;
17     sleep 5s ;
18    (call $dig_write (i32.const 16)
18     (i32.const 1)) ; on ;
19    (call $delay (i32.const 5000)) ;
19     sleep 5s ;
20    (br $begin))) ; jump back to start
20     of $begin loop ;

```

pinMode (pin,mode)	int × int → ()
digitalWrite (pin, value)	int × int → ()
digitalRead (pin)	int → int

Figure D-15. API and example of the WARDuino digital input-output.

faster than perceivable by the eye. The higher the duty cycle, the brighter the LED appears.

To control the modulator we provide three API functions: `setPinFrequency`, `analogWrite`, and `analogRead`. The interface for each of these functions is shown in figure Figure D-16. With `setPinFrequency` we can modify the frequency of a certain pin. For example when the default frequency on pin D1 is 31250 Hz a call to `(setPinFrequency D1 8)` will change the frequency on the pin to $31250/8$ Hz. Setting the duty cycle is done with `analogWrite`, an argument value of 0 corresponds to a duty cycle of 0%, the value 255 represents a duty cycle of 100%. Finally, the `analogRead` function measures the voltage on a certain pin and returns it as an integral value.

```

1  (module
2    ( ; fade function ;
3    (func $main (type $vd->vd)
4      (local $i i32) ( ; loop iterator ;
5      (call $pin_mode (i32.const 16) (i32.const 1))
6      (loop $infinite
7        (local.set $i (i32.const 0))
8        (loop $increment
9          (call $analog_write (i32.const 16) (local.get $i))
10         (local.set $i (i32.add (local.get $i) (i32.const 1)))
11         (i32.const 5)
12         (call $delay)
13         (br_if $increment ( ; jump to line 8 if i<255 ;
14           (i32.lt_s (get_local $i) (i32.const 255))))
15       (loop $decrement
16         (call $analog_write (i32.const 16) (local.get $i))
17         (local.set $i (i32.sub (local.get $i) (i32.const 1)))
18         (i32.const 5)
19         (call $delay)
20         (br_if $decrement ( ; jump to line 15 if i>0 ;
21           (i32.gt_s (local.get $i) (i32.const 0))))
22       (br $infinite)))

```

Figure D-16. *Left:* Example of the PWM module in WARDuino. *Top right:* PWM API of WARDuino.

D.3 Serial Peripheral Interface

The serial peripheral interface (SPI) is a bus protocol commonly used to communicate between a microcontroller and peripheral devices such as sensors, SD-cards, displays, and shift registers. The SPI communication protocol can be implemented in hardware or in software. When using the hardware implementation the programmer must use the dedicated SPI pins on the microcontroller. In software, the programmer is free to use any of the available input-output pins. Software implementations are however, significantly slower than making use of the hardware implementation.

WARDuino's primitives governing access to the hardware SPI bus are shown in figure Figure D-17. The functions `spiClockDivider`, `spi\Bit\Order`, `spiDataMode` are configuration functions to specify how data will be transferred. Before actually using the SPI bus the programmer first needs to call the `spiBegin` which initializes the SPI module. Once initialised, the programmer can start transferring data to the peripheral device by using one of the transfer functions. We included two kinds of transfer functions one for 8-bit transfers and one for 16-bit transfers. For both variants we included a bulk mode which sends the same data a specific number of times. The inclusion of the bulk operations can improve the performance of a display driver greatly.

Appendix D.3. Built-in Modules

spiBegin()	$\emptyset \rightarrow \emptyset$
spiBitOrder(bitorder)	$\text{int} \rightarrow \emptyset$
spiClockDivider(divider)	$\text{int} \rightarrow \emptyset$
spiDataMode(mode)	$\text{int} \rightarrow \emptyset$
spiTransfer8(data)	$\text{int} \rightarrow \emptyset$
spiTransfer16(data)	$\text{int} \rightarrow \emptyset$
spiBulkTransfer8(count,data)	$\text{int} \times \text{int} \rightarrow \emptyset$
spiBulkTransfer16(count,data)	$\text{int} \times \text{int} \rightarrow \emptyset$
spiEnd()	$\emptyset \rightarrow \emptyset$

Figure D-17. API of the WARDuino SPI module

```

1 (module
2   (memory $text 1)          ; Initialize
3     linear memory to one page ;
4
5   (data (i32.const 0) "WARDuino") ; place text
6     in memory at offset 0;
7
8   (func $main (type $vd->vd)
9     (i32.const 0) ; start index of string ;
10    (i32.const 8) ; string length ;
11    (call $print)))

```

print(string) print_int(value)	string $\text{int} \times \text{int} \rightarrow \emptyset$ $\text{i32} \rightarrow \emptyset$
---	---

Figure D-18. API and example code of the Serial module in WARDuino.

We have used the SPI module to implement a display driver in WARDuino. We leave out the specifics of that implementation here, not only for brevity, but because the code is originally written in C, rather than directly in WebAssembly like our other examples. We refer any interested reader to the first paper on WARDuino (Gurdeep Singh and Scholliers, 2019).

D.4 Serial Port Communication

Microcontrollers typically have at least one serial port. This port is used for flashing code to a microcontroller. Developers also regularly use this port for printing debug or log messages to a computer during development. The Arduino's Serial library is therefore indispensable for many programmers. We use it to add two print primitives to WARDuino to print numeric values and strings to the serial port. That latter feature is not as straightforward as it may seem because WebAssembly only supports basic numeric types, and not strings.

Fortunately, we can represent strings in WebAssembly by storing them as UTF-8 encoded bytes in WebAssembly's linear memory. Memory in WebAssembly is called linear memory because it is simply one long continuous buffer that can grow in increments of 64 kiB pages. Currently, WebAssembly only supports one memory per module, but memories are importable. Saving strings in memory is not enough, we also need a way to work with them, specifically, we need a way of referring to a string. To pass a string as an argument to a function, it can be represented as a tuple containing its offset in WebAssembly memory together with its length. This is illustrated in figure Figure D-18, which shows the interface of our two serial bus primitives. One primitive simply prints a numeric value, the other prints a string from linear memory. The example program on the left side of the figure shows how we can print a string to the serial port in WebAssembly. The code starts on line 2 by declaring a WebAssembly linear memory with the label \$text, followed by an initial size of one memory page (64 kiB). This is more than enough space to store the simple message in the data section on the next line. This section is similar to the data sections found in native executable files. The string is written at offset 0 in linear memory at initialization time. Not much more is needed to print the text in memory to the serial port, the main function simply places the indices and length of the string on the stack and calls the print primitive.

D.5 Wireless Networks

Applications for embedded devices often communicate with other devices. To accommodate this, many microcontrollers come with a Wi-Fi chip to connect to a wireless network. We have extended WARDuino with the necessary primitives for connecting to a wireless network. Because we use Arduino to implement these primitives in WARDuino, it makes sense to mirror the underlying Arduino interfaces for connecting. This way we do not unnecessarily introduce entirely new interfaces. Unsurprisingly, the Arduino functions use strings to specify parameters such as the network SSID and password. We represent those strings as pairs of integers as discussed in the section on the serial port communication module.

Figure Figure D-19 shows the interfaces of the wireless networking primitives on the right. Because these primitives take strings as arguments, the number of integer parameters can get relatively high. To keep the description of the API compact, we abbreviate long chains of the same type with the power notation. For instance, the connect primitive that connects to a Wi-Fi network has type $\text{int}^4 \rightarrow ()$. This notation represents four integer arguments, or two strings in this case, and no return value. The first string argument contains the SSID of the network to connect to, the second argument contains

Appendix D.5. Built-in Modules

```

1  (module
2    (; memory ;)
3    (memory $credentials 1)
4    (data (i32.const 0) "SSID")
5    (data (i32.const 6) "P4SSW0RD")
6
7    (; connect function ;)
8    (func $main (type $vd->vd)
9      (loop $until_connected
10        (i32.const 0) (; ssid start
11          address ;)
12          (i32.const 4) (; ssid string
13            length ;)
14          (i32.const 6) (; password start
15            address ;)
16          (i32.const 8) (; password string
17            length ;)
18          (call $connect)
19          (i32.ne (call $status) (i32.const
20            3)) (; true if failed ;)
21          (br_if $until_connected))
22        (i32.const 10)  (; arg1 of print:
23          buffer offset,      --- ;)
24        (i32.const 10)  (; arg1 of localip:
25          buffer offset,      | ;)
26        (i32.const 20)  (; arg2 of localip:
27          buffer length      | ;)
28        (call $localip)  (; return value
29          becomes arg2 of print --- ;)
30        (call $print)
31      ))
32    )

```

connect	ssid _{start} , ssid _{length}	int ⁴ → ()
	pass _{start} , pass _{length}	
status	()	() → int
localip	(ip _{start} , ip _{max_length})	int ² → int

Figure D-19. API and example code of the Wi-Fi module in WARDuino.
 $\text{int}^2 = \text{int} \times \text{int}$

the password used to authenticate. The status primitive returns an integer indicating the status of the network connection. If there is an active connection it will return 3. Our localip primitive retrieves the IP address of the device. This primitive takes two integer arguments representing a memory slice where a string can be stored. Because WebAssembly only supports one memory per module, the returned string needs to be saved in the memory defined by the module calling localip. To know where in this memory the primitive can safely write its string return value, we require a memory slice as argument. Once the IP address is written to the memory slice, localip returns the size of string it has written. This methodology is comparable to how C functions take a character buffer as an argument to write their result to.

A small piece of WebAssembly code that connects to a Wi-Fi network and prints the IP address is shown on the left of figure Figure D-19. The code

first declares a memory of one page (64 kB) and writes the network SSID and password to it (lines 3-5). The main function starts by connecting to the Wi-Fi network in the `$until_connected` loop (lines 9-16). At the start of the loop, const-instructions place the offsets and lengths of the two strings on the stack. Then we call the connect primitive, which tries to connect to the given network. The call blocks execution until it finishes or fails. We check whether a connection was successfully established by verifying that the status primitive returns 3 (connected). If not, the `br_if` instruction on line 16 jumps back to the start of the loop, and the program retries connecting to the network. Once connected, we print the IP address of the device by combining `localip` and `print`. The `localip` primitive returns the length of the string it wrote to the memory slice it received as argument, zero indicates a failure to retrieve the local IP address. Because WebAssembly is a stack based language, we can push the start index of the response buffer of `localip` to the stack before pushing the arguments to `localip`. When `localip` returns, it will have popped its two arguments off the stack and pushed the length of the IP address back to the stack. Now, the stack holds the right arguments for the `print` primitive once execution gets to line 21. If the `print` primitive gets a zero length argument it will simply not print anything, so we do not need to check in WebAssembly whether an IP address was actually retrieved.

D.6 Hypertext Transfer Protocol

The Hypertext Transfer Protocol (HTTP) (Fielding and Reschke, 2014) drives the modern web. Developers can use HTTP to access the entire web from a WebAssembly program running on a microcontroller with WARDuino. To keep the module small, we only add the most fundamental HTTP requests, GET, PUT, POST. As before, we give the interface of the primitives in figure Figure D-20. String arguments are given as pairs of integers representing memory slices. If the primitive returns a string, an extra pair of integers, pointing to a free slice of memory, is added to the arguments.

The code example in figure Figure D-20 prints an ASCII version of the Arduino logo retrieved from the internet with an HTTP GET request. To do this, it first adds the URL of the ASCII art logo in WebAssembly linear memory (lines 3-5). The main function will repeatedly retrieve the logo in an infinite loop that starts on line 8. Before the code pushes the four integers arguments for the `get` primitive, it pushes the start index of the response buffer onto the stack. This is the same trick we used in the previous example using the `print` primitive. By pushing this value now, and the `get` primitive pushing the length of the result, we can call the `print` primitive immediately without having to reorder the stack first. After the ASCII text has been printed to the

Appendix D.6. Built-in Modules

```

1  (module
2   ( ; Memory ; )
3   (memory $url 1)
4   (data (i32.const 0)
5     "http://www.arduino.cc/
6      asciilogo.txt")
7   (func $main (type $vd->vd)
8     (loop $loop
9       (i32.const 40) (;
10      response_start for print ;)
11      (i32.const 0) (; url_start ;)
12      (i32.const 35) (; url_length ;)
13      (i32.const 40) (;
14      response_start ;)
15      (i32.const 200) (;
16      response_length ;)
17      (call $get)
18      (call $print)
19      (i32.const 1000)
20      (call $delay)
21      (br $loop))))
```

get(url _{start} , url _{length}	int ⁴ → int
	response _{start} , response _{length})	
put(url _{start} , url _{length}	int ⁶ → int
	payload _{start} , payload _{length})	
	content type _{start} , content type _{length})	
post(url _{start} , url _{length}	int ⁸ → int
	payload _{start} , payload _{length})	
	content type _{start} , content type _{length})	
	response _{start} , response _{length})	

Figure D-20. API and example code of the HTTP module in WARDuino.

serial port, the microcontroller waits for 1 second before starting the entire procedure again.

D.7 MQTT Protocol

HTTP was designed for the web and is not optimized for an embedded context (Naik, 2017). More suitable protocols have been developed for IoT applications, such as the widely used MQTT (Banks and Gupta, 2014) protocol. This is one of the most mature and widespread IoT protocols at the time of writing. It is more lightweight in several aspects compared to HTTP. The message overhead is a lot smaller, since headers only require 2 bytes per message. Another important difference with the client-server approach of HTTP, is the client-broker architecture of MQTT. By using a publish-subscribe paradigm, MQTT reduces the number of messages a microcontroller needs to send. The publish-subscribe paradigm is commonly used in IoT contexts because its simplicity and effectiveness at reducing network traffic (Gupta and M, 2021, Sidna et al., 2020). The main idea of this paradigm is to disconnect communication in time and space. This means, that entities do not have to be reachable at the same time, and do not need to know each other, to communicate. Consequently, entities are free to halt execution or sleep. They may send and process messages whenever they choose to. This is the great advantage of MQTT over HTTP for constrained devices. We have added the basic MQTT

operations to WARDuino. The implementation is backed by Nick O’Leary’s⁷ Arduino library for MQTT messaging.

Because MQTT clients do not know each other, they communicate through a shared third party, the MQTT Broker. Communication starts when an MQTT client opens a persistent TCP connection with the MQTT Broker and sends an arbitrary string as its unique identifier to the server. Once connected, the MQTT client can both publish messages or subscribe to topics. The broker filters incoming (published) messages based on their topics and sends them asynchronously to every connected client subscribed to those specific topics. Topics need not be initialized, clients can send messages to any topic string of the right form.

The first four MQTT primitives shown on the right side of figure Figure D-21, are administrative. The `init` function sets the URL and port of the MQTT broker. By calling the `connect` primitive with a client ID string, represented by a memory slice, a connection is established. This primitive returns the status of the connection with the server (one if connected, else zero). We give developers full control over the frequency with which the device checks for new messages. They can trigger a check by calling our `poll` primitive without arguments. Such a call will process all incoming messages and invoke their callbacks, the return value is the status of the connection. The `poll` primitive needs to be called regularly to maintain the connection to the broker. Getting the connection status can also be done without processing messages by using the `connected` primitive.

The remaining primitives encompass the core MQTT operations: `subscribe`, `unsubscribe`, and `publish`. They all return a boolean value to indicate success (1) or failure (0). Our `subscribe` primitive takes a topic string, and the function index of a callback function that will handle any incoming message matching the specified topic. A callback function must be of the type `int4 → ()`. It takes two strings as argument: the topic and the payload of the received message. The callback function can interact with the memory of the module but must not return a value. To assign a function index to a function, it must be stored in a table of the WebAssembly module. The function index is simply its index in the callback’s table. Whenever a message arrives from the server for a subscribed topic, the appropriate callback functions will be executed by WARDuino. Our `unsubscribe` primitive permits removing specific callback functions from specific topics. If all callbacks to a topic are removed, the MQTT broker is informed that we no longer wish to get messages for that topic. Aside from subscribing to topics, we can also send payloads for topics to the MQTT Broker. This is done with the `publish`

⁷Documentation at: <https://github.com/knolleary/pubsubclient>

Appendix D.7. Built-in Modules

```

1  (module
2    (memory $url 1)
3    (data (i32.const 0)
4      "broker.hivemq.com")
5    (data (i32.const 20) "mcu")
6    (data (i32.const 25) "helloworld")
7
8    (; callback function ;)
9    (func $callback (type $int->int->int-
>int->vd)
10      (call $print (local.get 2) (local.get
11        3)))
12    (; add callback to table ;)
13    (table $callbacks 1 funcref)
14    (elem (i32.const 0) $callback) (; fid = 0 ;)
15
16    (; (re)connect function ;)
17    (func $reconnect (type $vd->vd)
18      (call $poll)
19      (loop $until_connected
20        (; connect to MQTT ;)
21        (i32.const 20)   (; client id start ;)
22        (i32.const 3)   (; client id length ;)
23        (call $connect)
24        (i32.ne (call $connected) (i32.const
25          1))
26        (br_if $until_connected)))
27
28    (func $main (type $vd->vd)
29      (i32.const 0)   (; url start ;)
30      (i32.const 17)  (; url length ;)
31      (i32.const 1883)  (; port ;)
32      (call $init)
33      (call $reconnect)
34
35      (loop $try_subscribing
36        (i32.const 25)  (; topic start ;)
37        (i32.const 10)  (; topic length ;)
38        (i32.const 0)  (; fidx ;)
39        (call $subscribe)
40        (i32.const 1)
41        (br_if $try_subscribing (i32.ne)))
42
43      (loop $waitloop
44        (call $delay (i32.const 1000))
45        (call $reconnect)
46        (br $waitloop))))

```

init(server_start, server_length, port)	int ³ → ()
connect(id_start, id_length)	int ² → int
poll()	() → int
connected()	() → int
subscribe(topic_start, topic_length, fidx)	int ³ → int
unsubscribe(topic_start, topic_length, fidx)	int ³ → int
publish(topic_start, topic_length payload_start, payload_length)	int ⁴ → int
Signature of MQTT callback functions:	
fn_name(topic_start, topic_length, payload_start, payload_length)	int ⁴ → ()

Figure D-21. API and example code of the MQTT module in WARDuino.

primitive that takes the same arguments as a callback function: a topic string, and a payload of the message to be published.

Figure Figure D-21 shows an example MQTT program on the left, which subscribes to the `helloworld` topic of an MQTT broker. Our small WebAssembly program will print the payload of each message it receives. The code starts by declaring all the static strings used in the program (lines 2-6). Our entry point is the main function defined on lines 26 to 44. First we initialize the MQTT module with the URL and port of the broker using the `init` primitive (27-30). Note that we have omitted the Wi-Fi connection code for brevity, as we have already shown how to connect to a Wi-Fi network in figure Figure D-19. Once our module is initialized, we connect it to the MQTT broker by using the `$reconnect` function. This function is defined on lines 16 to 24. It calls the administrative `poll` primitive and tries to connect to the broker until successful. After calling `$reconnect`, our main function continues by subscribing to the `helloworld` topic (lines 33-39). This is done in a loop labeled `$try_subscribing` which calls the `subscribe` primitive repeatedly until it returns 1 (success). In WebAssembly we cannot pass a function directly to another function. Instead, we must add the function to a table of function references. The code declares such a table of size one on line 12. On the next line the `element` section adds our callback function to the `$callbacks` table at index zero. This is the zero we use on line 36 to refer to it. Lines 9 to 10 define the callback function we stored in our table. It takes two arguments, a message topic and a payload. With the `local.get` instruction, the function places its last two arguments, corresponding to the payload string, on the stack and then it calls the `print` primitive. Our main function ends with an infinite loop on lines 41 to 44 that calls `$reconnect` every second to check if the connection is still live and reconnect if necessary.

E. Addendum to remote debugging with WARDuino

This appendix is an addendum to Chapter 3.

E.1 Over-the-air Updates Defined Orthogonally

The formalization of the over-the-air updates is presented in Section 3.8.4 as an addition to the remote debugger semantics (Section 3.8.2). However, we designed the update semantics to be orthogonal to the debugging system, making it easy to define a version of the over-the-air updates that does not rely on the remote debugger. The rules below show the update system as a standalone semantics on top of the WebAssembly semantics.

Syntax rules

$$\begin{array}{ll}
 (\text{UpdaterState}) \text{ upd} ::= \{\text{msg}_i, s\} \\
 (\text{Msg}) \qquad \text{msg} ::= \emptyset \mid \text{upload } m^* \mid \text{update}_f(\text{id}_i, \text{id}_f, \text{code}_f) \mid \text{update}_l(j, v) \\
 (\text{closures}) \qquad cl ::= \{\text{inst } i, \text{idx } j, \text{code } f\}
 \end{array}$$

Evaluation rules

$$\begin{array}{c}
 \frac{s; v^*; e^* \hookrightarrow_i s'; v'^*; e'^*}{\{\emptyset\}; s; v^*; e^* \hookrightarrow_{d,i} \{\emptyset\}; s'; v'^*; e'^*} \text{ VM-RUN} \\
 \frac{(\vdash m)^* \quad \{s'; v'^*; e'^*\} = \text{bootstrap}(m^*)}{\{\text{upload } m^*\}; s; v^*; e^* \hookrightarrow_{d,i} \{\emptyset\}; s'; v'^*; e'^*} \text{ UPLOAD-M} \\
 \frac{s' = \text{update}_f(s, \text{id}_i, \text{id}_f, \text{code}_f)}{\{\text{update}_f(\text{id}_i, \text{id}_f, \text{code}_f)\}; s; v^*; e^* \hookrightarrow_{d,i} \{\emptyset\}; s'; v^*; e^*} \text{ UPDATE-F} \\
 \frac{\vdash v : \epsilon \rightarrow t \qquad \vdash v' : \epsilon \rightarrow t}{\{\text{update}_l(j, v')\}; s; v_1^j v_2^k; e^* \hookrightarrow_{d,i} \{\emptyset\}; s'; v_1^j v' v_2^k; e^*} \text{ UPDATE-LOCAL}
 \end{array}$$

Figure E-22. The *step forwards* rules for input and output primitives in the multiverse debugger for WebAssembly, without input mocking. Addition to Figure 5-6.

All parts of the debugger semantics are removed, and a new vm-run rule is introduced. Contrary to the semantics shown in Section 3.8.2, the state s is now only extended with the incoming messages.

E.2 Microbenchmarks

Our microbenchmarks are implemented as described below.

tak a popular function from the Gabriel Benchmarks, contains an implementation of Takeuchi's tak function, specifically $\tau(18, 12, 6)$.

catalan computes various Catalan numbers. The n -th Catalan number is computed with: $C_n = \frac{1}{n+1} \binom{2n}{n}$. The benchmark implements this formula up to the 17th Catalan number (to avoid overflow).

fac implements a recursive implementation for calculating the integer factorial function. In the benchmark we calculate $(n \bmod 12)!$ for $n \in [0, 1000[$.

fib determines the value of the n^{th} Fibonacci number iteratively, for all $n \in [1000, 1050[$.

gcd computes the greatest common denominator of two numbers. In the benchmark we calculate the gcd of all whole numbers in $[4000, 5000[$ and 12454.

primes verifies if numbers are prime by looking for divisors. The benchmark consists of finding and calculating the sum of the first 127 primes.

F. Addendum to out-of-place debugging

This appendix is an addendum to Chapter 4.

F.1 Auxiliary out-of-place lemma

For the soundness of the stateful out-of-place debugger presented in Chapter 4, it is important that any remote action invocation follows the same three steps, first backward state synchronization with either the *step-transfer* or *run-transfer* steps, second the execution of the action on the server by the *invoke* step, and third the *sync* step to synchronize the state of the server with the client. The following lemma states that indeed any *sync* step is proceeded by the transfer and invoke steps.

To improve legibility, we write a step in the debugger that uses a specific evaluation rule with the name of the evaluation rule above the arrow, for instance $\xrightarrow{sync}_{d,i}$.

Lemma F-1. (Invoke uniqueness)

$$\begin{aligned} \forall \text{dbg} : \text{dbg}_{\text{start}} &\xrightarrow{*}_{d,i} \text{dbg}' \xrightarrow{sync}_{d,i} \text{dbg} \\ &\implies \\ \exists \text{dbg}''', \text{dbg}''' &: \text{dbg}'' \xrightarrow{step}_{d,i} \text{dbg}''' \xrightarrow{invoke}_{d,i} \text{dbg}' \\ \wedge (\text{step} = \text{step-transfer} \vee \text{step} = \text{run-transfer}) \end{aligned}$$

Proof Sketch. We can proof this lemma by contradiction. Assume first that the preceding step from dbg''' to dbg' is not an *invoke* step. However, since the *sync* step is the last step in the sequence, dbg' must contain a $\text{sync}(s, v)$ message in the message box of the client. This is only possible after an *invoke* step. Now, assume that *step* is not a *step-transfer* or a *run-transfer* step. However, since we already proved that the next step is *invoke*, we know that the message box in the server must contain an *invoke* message in dbg''' , which is not possible with any other rules. \square

F.2 Debugging concurrency issues

Apart from the device related bugs discussed in Section 4.8.5, software development issues are common in IoT applications (Makhshari and Mesbah, 2021). Within this type, a common root cause is concurrency faults

(Makhshari and Mesbah, 2021). Listing F-1 shows the implementation of a smart lamp application in AssemblyScript. The code allows users to control the brightness of an LED with MQTT messages or two hardware buttons. The application listens for messages on topics, *increase* and *decrease* (lines 55 - 58). For each message, the code increases or decreases the brightness of the LED by five percent, respectively. Instead of changing the brightness abruptly, the code gradually changes the brightness. For this reason, the callback function does not directly change the LED brightness, but it changes the variable `delta` to record the requested change. The function `updateBrightness` called in the main application loop changes the actual brightness gradually. Every time it is called, it changes the brightness by one percent in the direction dictated by the sign of `delta`. After doing this, the absolute value of `delta` is lowered by one. In this way, the application only needs to check the value of the `delta` variable and change the brightness whenever it does not equal zero (line 64).

The Bug. When testing this program with a real hardware setup, the developer notices that the brightness changes irregularly. When sending two messages to the *increase* topic, the LED increases its intensity by only 5% instead of 10%. The reason is that the second message overwrites the value of the `delta` variable before the `updateBrightness` function updates the LED. Such concurrency bugs are often time sensitive, and do not always manifest (McDowell and Helmbold, 1989). In our example the bug only manifests when sending two MQTT messages rapidly. This made finding the exact conditions for the bug very difficult. Moreover, the effects of the bug can happen long after the root cause (Perscheid et al., 2017), i.e. when the main loop updates the brightness.

Bugfixing with a Remote Debugger. As mentioned before, stepping through code with asynchronous callbacks using current state of the art remote debuggers is very difficult. The developer has no control over when the asynchronous callbacks are called. This makes it difficult to reproduce the exact conditions in which the bug manifest. In turn, this increases the times a developer needs to manually step through the application before reproducing the error, drastically complicating debugging. Moreover, the developer needs to keep track of all the steps taken and remember these steps carefully for when the bug manifest later, and a new debugging session is needed. Finally, stepping through the code is relatively slow due to network latency between the developer's machine and the remote device.

Bugfixing with Edward. *Edward* can help debugging these concurrency bugs thanks to its event scheduling and time-traveling debugging features. By using EDWARD, developers can inspect the generated events and schedule their execution one after another (as the developer suspects that this is when

```

1 import * as wd from "warduino";
2
3 const LED: i32 = 10;
4 const MAX_BRIGHTNESS: i32 = 255;
5 const UP_BUTTON: i32 = 37;
6 const DOWN_BUTTON: i32 = 39;
7 const CHANNEL: i32 = 0;
8 const SSID = "local-network";
9 const PASSWORD = "network-password";
10 const CLIENT_ID = "random-mqtt-client-id";
11
12 let brightness: i32 = 0;
13 let delta: i32 = 0;
14
15 function until_connected(connect: () => void,
16                           connected: () => boolean): void {
17     while (!connected()) {
18         wd.delay(1000);
19         connect();}}
20
21 function check_connection(): void {
22     until_connected(
23         () => { wd.mqtt_connect(CLIENT_ID);
24                 wd.mqtt_loop(); },
25         () => { return wd.mqtt_connected(); });
26 }
```

Listing F-1. The full code of the example application illustrating a concurrency problem in Internet of Things.

the bug manifests). When they step through the code, they can visually inspect the brightness of the LED and observe that the bug has indeed manifested. If the root cause was not discovered during the initial debugging session the developer can easily step back in time and go through the code as many times as needed. During this time-traveling debugging session they can then notice that when receiving two messages in a row, the second may overwrite the `delta` parameter set by the first message before it was processed by the main loop, revealing the cause of the bug. Lines 59 and 61 should increase (and decrease) the value of `delta` instead of overwriting it.

```
27 function init(): void {
28     wd.analogSetup(CHANNEL, 5000, 12);
29     wd.analogAttach(LED, CHANNEL);
30
31     // Connect to Wi-Fi
32     until_connected(
33         () => { wd.wifi_connect(SSID, PASSWORD); },
34         () => { return wd.wifi_status() == wd.WL_CONNECTED; });
35     let message = "Connected to wifi network with ip: ";
36     wd.print(message.concat(wd.wifi_localip()));
37
38     // Connect to MQTT broker
39     wd.mqtt_init("192.168.0.24", 1883);
40     check_connection();
41
42     function updateBrightness(): void {
43         brightness += delta;
44         if (brightness < 0) {
45             brightness = 0;
46         }
47         if (brightness > MAX_BRIGHTNESS) {
48             brightness = MAX_BRIGHTNESS;
49         }
50         wd.analogWrite(CHANNEL, brightness, MAX_BRIGHTNESS);
51         delta = 0;
52     }
53
54     export function main(): void {
55         init();
56
57         // Subscribe to MQTT topics and turn on LED
58         wd.mqtt_subscribe("increase",
59             (topic: string, payload: string) => {delta = 5});
60         wd.mqtt_subscribe("decrease",
61             (topic: string, payload: string) => {delta = -5});
62         while (true) {
63             check_connection();
64             if (delta !== 0) updateBrightness();}}
```

Listing F-2. Listing F-1 continued.

G. Auxiliary multiverse debugger rules

In this appendix, we present the auxiliary debugger rules for the multiverse debugger for WebAssembly, omitted from Chapter 5 in the main text for brevity. These are the rules for the step forward operations on primitive calls, and the run variant of the *step-mock* rule.

Auxiliary evaluation rules

$$\begin{array}{c}
 \frac{K_n = \{s; v^*; v_0^*(\text{call } j)\} \quad P(j) = p \quad p \in P^{In} \quad \text{mocks}(j, v_0^*) = \varepsilon}{K_n \hookrightarrow_i K_{n+1}} \text{step-prim-in} \\
 \hline
 (\text{pause}, \text{step}, \text{mocks}, K_n \mid S^*) \hookrightarrow_{d,i} (\text{pause}, \emptyset, \text{mocks}, K_{n+1} \mid S^* \cdot \{K_{n+1}, r_{nop}\})
 \end{array}$$

$$\begin{array}{c}
 \frac{K_n = \{s; v^*; v_0^*(\text{call } j)\} \quad P(j) = p \quad p \in P^{Out} \quad p(v_0^*) = \{\text{ret } v, \text{cps } r\}}{K_{n+1} = \{s; v^*; v\}} \text{step-prim-out} \\
 \hline
 (\text{pause}, \text{step}, \text{mocks}, K_n \mid S^*) \hookrightarrow_{d,i} (\text{pause}, \emptyset, \text{mocks}, K_{n+1} \mid S^* \cdot \{K_{n+1}, r\})
 \end{array}$$

Figure G-23. The *step forwards* rules for input and output primitives in the multiverse debugger for WebAssembly, without input mocking. Addition to Figure 5-6.

Auxiliary evaluation rules

$$\begin{array}{c}
 \frac{K_n = \{s; v^*; v_0^*(\text{call } j)\} \quad P(j) = p \quad p \in P^{In} \quad \text{mocks}(j, v_0^*) = v}{K'_{n+1} = \{s'; v'^*; v\}} \text{run-mock} \\
 \hline
 (\text{play}, \emptyset, \text{mocks}, K_n \mid S^*) \hookrightarrow_{d,i} (\text{play}, \emptyset, \text{mocks}, K'_{n+1} \mid S^* \cdot \{K'_{n+1}, r_{nop}\})
 \end{array}$$

Figure G-24. The register and unregister rules for input mocking in the MIO multiverse debugger, as well as the *run-mock* variant. Addition to Figure 5-9 from Section 5.3.7.

H. Proofs and auxiliary lemmas for the multiverse debugger

In this appendix, we present the lemmas and proofs for the multiverse debugger semantics for WebAssembly, omitted from Section 5.3.9. The first lemma states that the mocking of input values will not introduce states in the multiverse debugger that cannot be observed by the underlying language semantics.

Lemma H-1. (Mocking non-interference) Given a debugging state dbg and $dbg \hookrightarrow_{d,i} dbg'$, which uses the *step-mock* rule, and K in dbg , and K' in dbg' , it holds that

$$dbg \hookrightarrow_{d,i} dbg' \implies K \hookrightarrow_i K'$$

Proof sketch. Since the *register-mock* rule only adds a new value to the *mocks* map when the value is in the codomain of the primitive, the value produced by the *step-mock* can be chosen by the non-deterministic rule *input-prim*.

□

A second lemma crucial to the soundness of the debugger, states that for any debugging state, there is a path in the underlying language semantics from the start to every snapshot in the snapshot list.

Lemma H-2. (Snapshot soundness) For any debugging state dbg with program state K_m , and snapshots S^* , it holds that

$$dbg_{\text{start}} \hookrightarrow_{d,i}^* \{es, msg, mocks, K_m, S^*\} \implies \forall \{K_n, r\} \in S^* : K_0 \hookrightarrow_i^* K_n$$

Proof sketch. By induction over the snapshots in the steps in $dbg_{\text{start}} \hookrightarrow_{d,i}^* \{es, msg, mocks, K_a, S^*\}$.

Base case: We have $S^* = \{K_0, r_{\text{nop}}\}$, and the lemma holds trivially since $K_0 \hookrightarrow_i^* K_0$.

Induction case: By the induction hypothesis, $dbg_{\text{start}} \hookrightarrow_{d,i}^* \{es', msg', mocks', K_m, S'^*\}$, and $\forall \{K_n, r'\} \in S'^* : K_0 \hookrightarrow_i^* K_n$. Now we prove the theorem still holds after:

$$\{es', msg', mocks', K_m, S'^*\} \hookrightarrow_{d,i} \{es, msg, mocks, K_a, S^*\}$$

The possible steps fall in five cases.

1. For the rules that do not change the snapshot list, *run*, *step-forwards*, *pause*, *play*, *register-mock*, *unregister-mock*, or *step-back*, the theorem holds trivially.
2. For the rules *run-prim-in* and *step-prim-in*, $K_a = K_{m+1}$, and the rules extend the snapshot list with $\{K_{m+1}, r_{nop}\}$. We know by the assumptions of the rule that $K_m \hookrightarrow_i K_{m+1}$, so the theorem holds.
3. For the rules *run-prim-out* and *step-prim-out* $K_a = K_{m+1}$, and the rules extend the snapshot list with $\{K_{m+1}, r\}$. Both rules satisfy the assumptions for the underlying language rule *output-prim*, and the state K_{m+1} is exactly the same as the state reached by *output-prim*. So we have $K_m \hookrightarrow_i K_{m+1}$, and the theorem holds.
4. The rule *step-mock* adds $\{K_{m+1}, r_{nop}\}$ to the snapshot list, $K_a = K_{m+1}$, and we know that $K_m \hookrightarrow_i K_{m+1}$ by Lemma H-1, so the theorem holds.
5. The *step-back-compensate* rule only removes a snapshot from the snapshot list, so by the induction hypothesis, the theorem holds.

□

Now we give the proof for debugger soundness, where the snapshot soundness lemma will be crucial.

Theorem H-1. (Debugger soundness) Let K_0 be the start WebAssembly configuration, and dbg the debugging configuration containing the WebAssembly configuration K_n . Let the debugger steps $\hookrightarrow_{d,i}^*$ be the result of a series of debugging messages, where msg is the last message. Then:

$$\forall \text{dbg} : \text{dbg}_{\text{start}} \hookrightarrow_{d,i}^* \text{dbg} \implies K_0 \hookrightarrow_i^* K_n$$

Proof sketch. By induction over the steps in the path $\text{dbg}_{\text{start}} \hookrightarrow_{d,i}^* \text{dbg}$.

Base case: We have $\text{dbg}_{\text{start}} = (\text{pause}, msg, \lambda z. \lambda y. \lambda x. \epsilon, K_0 \mid \{K_0, r_{nop}\})$, and the length of the path is 1. The rules *run*, *pause*, *run-prim-in*, *run-prim-out*, do not apply since the execution state is not *play*. Similarly, the *step-back* and *step-back-compensate*, do not apply since the index label for K is zero, and *step-mock* does not apply because the mocking map is empty. The rules *play*, *register-mock*, and *unregister-mock* do not change the state K_0 , and $K_0 \hookrightarrow_i^* K_0$ holds for length 0. The *step-forwards* and the *step-prim-in* rules use the underlying language semantics to step to K_1 . Finally, the requirements for the *output-prim* in the underlying language semantics are met by the *step-*

prim-out rule. The *step-prim-out* rule moves the state to $K_1 = \{s, v^*, v\}$, which is exactly the same state reached by the *output-prim* rule in the underlying language semantics. So the theorem holds for the base case.

Induction case: We have a debugging state dbg' with WebAssembly state K' , we know that $dbg_{\text{start}} \hookrightarrow_{d,i}^* dbg'$ holds, and there is a step $dbg' \hookrightarrow_{d,i} dbg$. Since dbg' can have any execution state, any message, and any mocking map, we need to consider all possible cases. For the rules which do not change the state K , the *play*, *pause*, *register-mock*, and *unregister-mock* rules, and the theorem holds trivially. For the *run*, *step-forwards*, *run-prim-in*, *step-prim-in*, by the induction hypothesis we know that $K_0 \hookrightarrow_i^* K'$, and the rules take the step $K' \hookrightarrow_i K$, so the theorem holds. If the mocking map returns a mocked value, the *step-mock* rule applies, and given the induction hypothesis and Lemma H-1, the theorem holds. However, stepping backwards is more complex. In case the final step uses *step-back*, the rule jumps to a state K_n from the snapshot list. By Lemma H-2, we know that $K_0 \hookrightarrow_i^* K_n$. Since in the assumptions of the *step-back* rule, we know that $K_n \hookrightarrow_i^{m-n-1} K_{m-1}$, the theorem holds. The case for the *step-back-compensate* rule is identical. \square

Theorem H-2. (Debugger completeness) Let K_0 be the start WebAssembly configuration for which there exists a series of transition \hookrightarrow_i^* to another configuration K_n . Let the debugging configuration with K_n be dbg . Then:

$$\forall K_n : K_0 \hookrightarrow_i^* K_n \implies dbg_{\text{start}} \hookrightarrow_{d,i}^* dbg$$

Proof sketch. For any step $K \hookrightarrow_i K'$ in the path $K_0 \hookrightarrow_i^* K'$, either we can apply the *step-forward* or *step-prim-out* rules to the debugging state dbg with state K . Or, K is a call to an input primitive, in which case $K \hookrightarrow_i K'$ is non-deterministic. However, since we know the return value v in K' , we can apply the *register-mock* rule, after which, the *step-mock* rule is applicable. This rule will move the state to $K'' = \{s; v^*; v\}$, which is the same as K' . So the theorem holds for all steps in the path $K_0 \hookrightarrow_i^* K'$.

\square

Finally, we give the proof for compensation soundness (Theorem 5-3). But first, for completeness, we provide the definition of external effects equivalence for a series of debugging rules and a series of rules in the underlying language semantics.

Definition H-1. (External effects equivalence) Let t be a series of rules in the debugging semantics, and q a series of rules in the underlying language semantics. When for each *step-prim-out* with p in $\text{external}(t)$, either the next *step-back-compensate* in $\text{external}(t)$ uses p_{cps} , or there is an *output-prim* with p in $\text{external}(q)$, we say that

$$\text{external}(t) \equiv \text{external}(q)$$

Theorem H-3. (Compensation soundness) Let K_0 be the start WebAssembly configuration, and dbg the debugging configuration containing the WebAssembly configuration K_n . Let the debugger steps $\hookrightarrow_{d,i}^*$ be the result of a series of debugging messages. Then:

$$\forall \text{dbg} : \text{external}(\text{dbg}_{\text{start}} \hookrightarrow_{d,i}^* \text{dbg}) \equiv \text{external}(K_0 \hookrightarrow_i^* K_n)$$

Proof sketch. The multiverse tree is a connected acyclic graph, where each edge is a step in the underlying language semantics. Any debugging session $\text{dbg}_{\text{start}} \hookrightarrow_{d,i}^* \text{dbg}$ can be seen as a walk over the multiverse tree, where edges can be visited more than once, and walking over an edge has a direction. By debugger soundness (Theorem 5-1), we know that for any debugging session there is a path in the underlying language semantics $K_0 \hookrightarrow_i^* K_n$. The debugging session constructed in the proof for the debugger completeness (Theorem 5-2), shows that for any path in the underlying language semantics, there is a debugging session P that ends in K_n , but does not use the *step-back* or *step-back-compensate* rules. This walk P corresponds to the path from K_0 to K_n in the multiverse tree, which only visits each edge once. This means that:

$$\text{external}(P) = \text{external}(K_0 \hookrightarrow_i^* K_n)$$

Now we can show that any walk over the multiverse tree that ends in state dbg can be reduced to the path P by only removing closed walks. Take a state dbg' on the path from $\text{dbg}_{\text{start}}$ to dbg . Say that step s is the first step in the debugging session that ends in the state dbg' , and s' is the last step to end in the state dbg' . Then the steps between s and s' must form a closed walk, and we know that no step will come back to dbg' . This holds for each state on the path, and therefore the entire session can be reduced to a path. Removing a closed walk has no effect on the external world, since each forward visit of an edge will have a corresponding backward visit in the walk. In other words, the effect on the environment by a closed walk is equivalent to the empty list. This means that:

$$\text{external}(P) = \text{external}\left(\text{dbg}_{\text{start}} \hookrightarrow_{d,i}^* \text{dbg}\right)$$

Therefore, the theorem holds. □