

RubiCL, a Library Providing Automatic Parallelisation on CPU and GPU devices.

Aaron Cronin

MInf Project (Phase 2) Report

Master's Informatics

School of Informatics

University of Edinburgh

2014

Abstract

This project presents a library that automates the parallelisation of several higher-order functions, originally provided within the Ruby standard-library. The library distributes computation across many compute-units, following an annotation specifying that primitives are solely operating on numerical data. RubiCL harnesses the OpenCL framework in order to allow execution to occur on CPU or GPU devices.

The library provides a simple interface to parallel processing, without the need for the user to specify orchestration specifics. This reduces barriers-to-entry concerning the exploitation of massively-parallel hardware. Utilising the development system's APU, the project achieved an execution speed-up of up to 9 times the standard Ruby implementation of higher-order computation pipelines. System performance was benchmarked and presented over a variety of task formulations, target systems, and input-data quantities.

Acknowledgements

I would like to thank the project's supervisor, Stratis Viglas, for providing technical guidance throughout the project's lifetime.

I would also like to thank my final-year flatmates, James Hulme and Jacob Essex. They both worked far too hard over the course of this year and were a significant motivation, as I strived to keep up with their relentless pace of study.

Table of Contents

1	Motivation	1
1.1	Introduction	1
1.1.1	The need for parallelism	1
1.1.2	Prevalence of parallelism	2
1.1.3	The holy grail of automatic parallelisation	3
1.1.4	Embarrassing parallelism	3
1.2	Related Work	4
1.2.1	MARS	4
1.2.2	HadoopCL	5
1.2.3	CUDAfy.NET	6
1.2.4	Data.Array.Accelerate	6
1.3	Synopsis	7
1.3.1	Recap of motivations for research	7
1.3.2	Brief description of proposed solution	7
2	Overview	9
2.1	Project Aims	9
2.1.1	Improving the performance of dynamic languages when executing data-driven tasks	9
2.1.2	Facilitating a larger scale of experimentation in a REPL environment by non-expert users	10
2.1.3	Exploring the extensibility of the Ruby programming language	11
2.1.4	Effective code generation and reuse on the OpenCL platform	11
2.1.5	Applicability to a variety of platforms, avoiding over-tailoring for a specific machine	12
2.2	Leveraged Software Components	12
2.2.1	OpenCL	12
2.2.2	Ruby	16
2.3	Project Progression	17
2.3.1	Timeline	17
2.3.2	Difficulties	20
2.4	Completed Work	21

3	Design	23
3.1	System architecture	23
3.1.1	Interface	23
3.1.2	Software architecture	25
3.1.3	Interacting with hardware devices	29
3.2	Design choices	32
3.2.1	Type annotation	32
3.2.2	Eager or deferred task dispatching	33
3.2.3	Construction and processing of tuple datasets	33
4	Implementation	35
4.1	Differences between CPU and GPU hardware	35
4.2	Parallel primitives	36
4.2.1	Map	36
4.2.2	Scan	38
4.2.3	Scatter	39
4.2.4	Filter	41
4.2.5	Count	44
4.2.6	Sort	44
4.3	Management System	44
4.3.1	Converting between Ruby and C objects	44
4.3.2	Transferring data to and from the compute-device	45
4.3.3	Function parser	46
4.3.4	Task queue	48
4.4	Functionality Testing	50
4.5	Performance testing	50
4.5.1	Custom benchmarking environment	51
4.5.2	Segmented timing information from execution environment	52
5	Evaluation	55
5.1	Recap of project aims	55
5.1.1	Objective goals	55
5.1.2	Subjective goals	56
5.2	Benchmarking	56
5.2.1	Range of tests	56
5.2.2	Test systems	56
5.2.3	Variety of data-types	59
5.2.4	Method	60
5.2.5	Issues	61
5.3	User Evaluation	61
5.3.1	Subjects	61
5.3.2	Method	62

TABLE OF CONTENTS

6 Results	67
6.1 Benchmarks	67
6.1.1 Map tasks	67
6.1.2 Dense Filter tasks	74
6.1.3 Sparse Filter tasks	80
6.1.4 MapFilter tasks	86
6.1.5 Sort tasks	92
6.2 User evaluation	95
6.2.1 Results	95
6.2.2 Test demographics	95
6.2.3 Observations made	95
6.2.4 Solution performance	97
6.3 Portability	97
7 Conclusions	99
7.1 Success of the project at achieving its aims	99
7.1.1 Improving the performance of dynamic languages when executing data driven tasks	99
7.1.2 Facilitating a larger scale of experimentation in a REPL environment by non-expert users	100
7.1.3 Exploring the extensibility of the Ruby programming language	100
7.1.4 Effective code generation and reuse on the OpenCL platform	101
7.1.5 Applicability to a variety of platforms, avoiding over-tailoring for a specific machine	101
7.2 Further work	102
Bibliography	

Chapter 1

Motivation

1.1 Introduction

1.1.1 The need for parallelism

Over the previous few decades, a trend of ever-increasing hardware clock-speeds has fuelled developer complacency. The often-cited “Moore’s Law” [1] suggested that our favourite algorithms will scale with demand, as executing systems increase in performance alongside complexity.

The stark truth is that this trend now seems to have lapsed (Figure 1.1). The latest generation of Central Processing Units (CPUs) offer no significant clock-speed improvements over the previous. Furthermore, increases in per-clock performance are lacklustre. Physical hardware constraints are to blame for this disappointment. Namely, higher-than-anticipated levels of interference between subcomponents as a result of vastly increased circuit densities.

To combat this stall, hardware manufacturers have responded by increasing the number of independent execution units, or *cores*, present on produced system components. As a result, the total throughput available on any given class of device has continued to improve. Today’s data-driven economy generates computational problems of relentlessly increasing size. Therefore, software engineers must adapt to utilise this increased core-count.

Unfortunately, this tactic of improving performance, by presenting a greater number of compute-units, is often incompatible with traditional programming approaches. The inapplicability of many tried-and-tested sequential architectural patterns forces engineers to consider new ones.

Constructing a parallel solution requires the study of new concepts, such as synchronisation and data dependencies. The next generation of software engineers are becoming familiar with these issues, but there is currently a significant knowledge-gap.

The necessary switch to parallel programming is not going as smoothly as desired. A short term solution for easing this transition is to provide common developers with the capability to easily utilise all compute-units within a system.

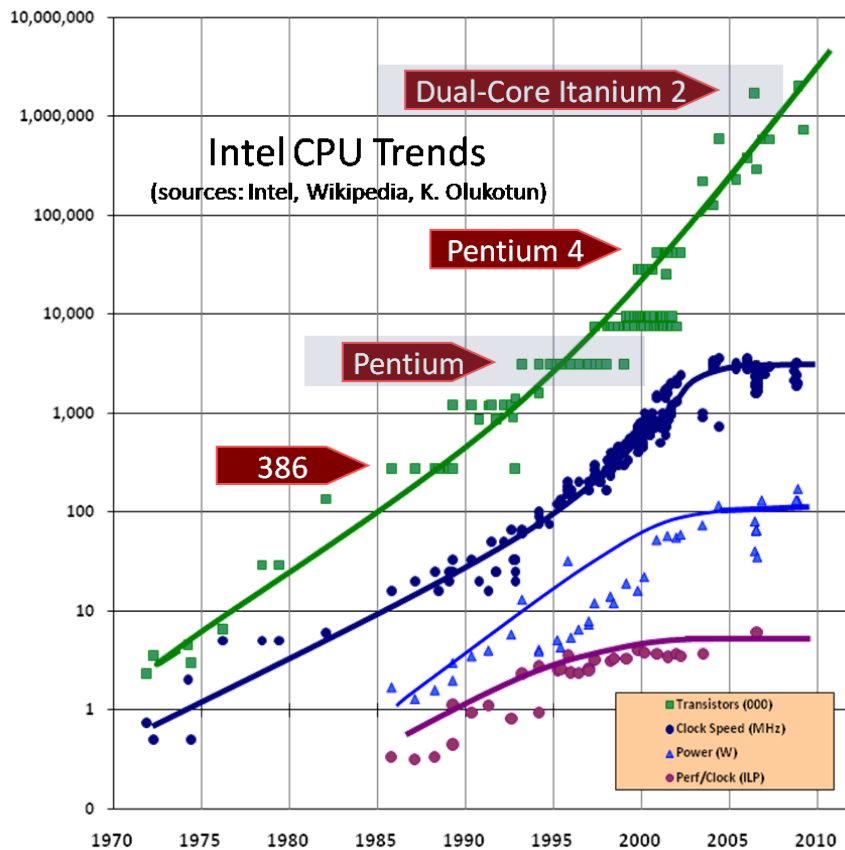


Figure 1.1: Graph demonstrating the recent plateau in clock-speed increase and performance-per-clock. Source: [2]

1.1.2 Prevalence of parallelism

As of 2014, many desktop machines contain 4-core CPUs, capable of scheduling 8 hardware threads simultaneously through a technology termed *Hyper-Threading*[3]. Depending on whether vendors are aiming for performance or portability, typical laptop systems contain between 2 and 4 cores. Most commodity systems will attempt to improve performance by scheduling a user's tasks across underutilised cores, in order to avoid preemption. This still leaves sequential algorithms facing the bottleneck of a single core's rate of computation.

The other common source of potential parallelism within a system results from advances in computer graphics. Graphics Processing Units (GPUs) are usually responsible for performing various computational stages of the graphics pipeline. They are highly parallel devices, tailored for high performance manipulation of pixel data. The popularity of playing games on home computers has led demand for increasingly powerful GPUs, producing a more responsive experience for consumers.

In recent generations, hardware manufacturers have explored combining specialised processing units, such as GPUs, along with CPUs on a single die. These hybrid devices, known as Accelerated Processing Units (APUs), often boast high transfer rates between components. They often allow modest graphical performance within a portable, low power device. As such, many laptops will contain an APU instead of two discrete devices.

System	Components	Discrete device count
Desktop (pre 2010)	CPU and GPU	2
Desktop	APU and GPU	3
Portable laptop	APU	2
Headless server	CPU	1

Figure 1.2: Components capable of parallel code execution, present in typical systems.

Several libraries have been developed to facilitate computation on hardware previously reserved for the graphics pipeline. As a result, the practice of employing GPUs for the task of executing custom code, in addition to their traditional roles, is often referred to as General-Purpose computation on Graphics Processing Units (GPGPU). Lately, there has been a noticeable increase of interest in GPGPU and its suitability for common data-driven problems.

In short, most conventional computer systems purchased today will contain more than one available parallel processing device. A selection of common, parallel hardware configurations are detailed in Figure 1.2.

1.1.3 The holy grail of automatic parallelisation

Improvements in language design and compilation are areas of study hoping to increase the magnitude of parallel execution in the wild, without requiring user interaction. Researchers are investigating the feasibility of discovering parallelism, inherent in user code, through analysis [4]. Whilst some breakthroughs have been made, progress is slow due to the massive complexity of the task. Languages with user-managed memory are hard to perform dependency analysis on correctly. In addition, the seemingly limitless variety of user programs greatly complicates any blanket solution.

It is likely that automatic parallelisation compilers will not become useful to any average developer in the near future.

However, automatic parallelisation of code can be achieved if the scope of attempted transformation is reduced. In certain software paradigms, there is low-hanging fruit that can feasibly be parallelised automatically. This provides a stop-gap solution whilst research continues.

1.1.4 Embarrassing parallelism

Some problems are inherently parallel, containing no dependencies between subtasks. They can be dissected into a set of distinct work-units that can be executed concurrently. Such tasks are referred to as “embarrassingly parallel”.

Many *functional programming* primitives, such as *Map*, are embarrassingly parallel, or parallelisable at some level of granularity. When transforming a dataset, any operation where the resultant state of each element in the output only depends on a single input can be easily scheduled across many compute-units.

Other tasks are more complicated, and require structuring as the composition of concurrent sub-

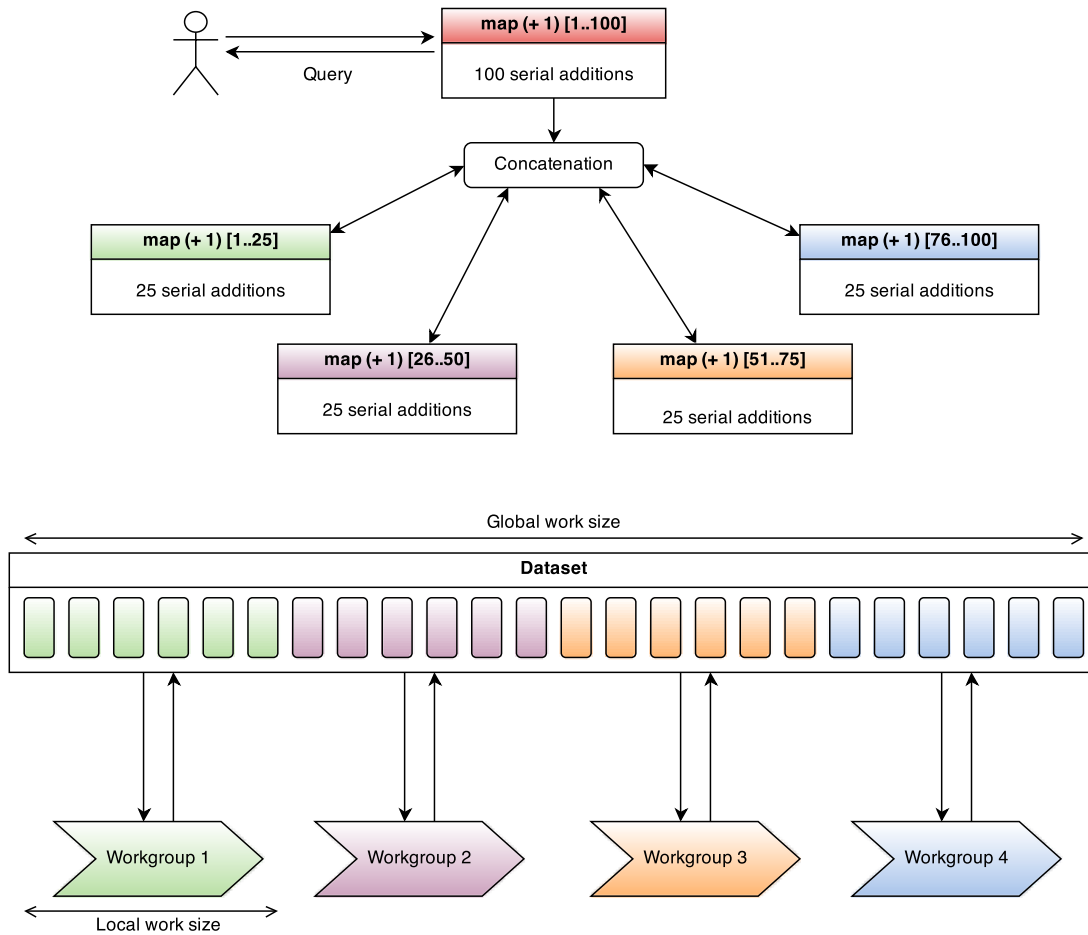


Figure 1.3: A partitioning of *map* computation over several compute-devices.

tasks. In the worst case, computing a result requires communication and synchronisation between parallel subproblems.

When manually parallelising code, programmers must become familiar with designing multithreaded algorithms. Subcomponents that cooperate must be produced in order to achieve processing speed-up.

This effort is often unnecessary. Certain primitives are known to be suitable for parallel execution. These can be algorithmically scheduled across multiple compute-units. By automating this translation and scheduling task, programmers can achieve increased throughput without the need for extensive studying and configuration.

1.2 Related Work

1.2.1 MARS

The MARS[5] project provides a MapReduce[6] run-time, executing on GPU systems. It aims to take advantage of the significant computational resources available on GPU devices. To utilise

available graphics hardware, it uses NVIDIA's Compute Unified Device Architecture (CUDA) library. It is one of the earliest research papers presenting the idea of dispatching general-purpose tasks to GPU hardware.

MARS attempts to overcome key obstacles, faced when trying to produce a GPU computing platform. A GPU's high throughput, provided by its massively parallel structure, is only maintained if task idling is avoided. In addition, mapping of work units must avoid cores becoming under-utilised and producing artificial critical paths. Balancing tasks and scheduling them effectively is important. MARS demonstrates a procedure for load-balancing work-units across GPU devices in order to avoid such idling.

One shortcoming of MARS is its reliance on the MapReduce computation pattern for general purpose tasks. MapReduce is well suited to computation on large quantities of unstructured data. However, when execution is constrained to a single device host, the redundant infrastructure provided by the run-time is no longer beneficial. The communication pattern can produce unnecessary overhead.

Another disadvantage of MARS is the need to write the individual task code as CUDA source files. This is inconvenient for any programmer lacking prior knowledge of parallel programming. To utilise MARS effectively, you must first become familiar with CUDA programming.

Divergences Instead of taking a large-scale computation pattern and mapping it to GPU architectures, this project will start by providing interfaces to primitive operations that such devices are suited for. A suite of expressive operations, composed from efficient subcomponents will then be produced.

Following this work-flow should enable the finished library to achieve a significant performance benefits, as it centres around tasks that the target hardware is well suited to.

1.2.2 HadoopCL

HadoopCL[7] is an extension to the Hadoop[8] distributed-filesystem and computation framework. Again, it provides scheduling and execution of generic tasks on GPU hardware. Since it uses Open Compute Language (OpenCL), as opposed to CUDA, it also supports execution on CPU devices.

One benefit, for usability, of HadoopCL over MARS is the usage of the `aparapi` library[9] to generate the required task kernels. Often, composing and scheduling custom OpenCL kernels requires a significant amount of boilerplate code. HadoopCL's Application Programming Interface (API), presented as a Java library, allows programmers to skip a large portion of this boilerplate and focus instead on the task at hand.

The fact that the interface resembles threaded Java programming is another plus. However, it still requires that functions are written containing logic guided by the notion of kernel execution ids. This does not mitigate the need to become familiar with a new paradigm for data-parallel computation. Therefore, the system is still not suitable for novice users.

Divergences Instead of presenting an interface for programmers to write OpenCL code via shortcuts, the RubiCL project will boast the ability to automatically transform and parallelise simple computational primitives written in Ruby code. This may suffer from reduced flexibility, but benefits from a significantly lower barrier-to-entry for inexperienced users.

Yet, constraining the user to the MapReduce computation pattern also reduces flexibility. The lack of arbitrary kernels for common tasks is not a significant drawback as long as any parallel task primitives are varied and composable.

1.2.3 CUDAfy.NET

The stated goal of the CUDAfy.NET[10] project is to allow “easy development of high performance GPU applications completely from the Microsoft .NET framework”.

Despite the name, CUDAfy.NET supports the OpenCL platform as a target back-end, in addition to CUDA.

CUDAfy completely bypasses the need to write custom kernel code, either directly crafted or indirectly generated through an API. It performs code generation by examining the source code of dispatched methods at run-time, translating the Common Language Runtime (CLR) bytecode to generate equivalent CUDA or OpenCL kernels.

CUDAfy benefits from significantly increased usability, as it generates OpenCL kernels on behalf of the programmer. However, it does not have a high enough level of abstraction to avoid necessarily impacting the calling code’s structure. The programmer’s workflow is still vastly altered when parallelising calculations. Anyone writing parallel CUDAfy code must concern themselves with explicitly detecting on-board devices. In addition, the transfer of data to and from a CPU/GPU compute-device must be triggered manually.

Divergences Instead of requiring explicit device and memory management, this project aims to automate these tasks. This ensures that programmers do not have to concern themselves with such concepts in order to parallelise computation. It should be sufficient to solely provide the calculations that are to be executed, after optionally stating that code should run on a particular device. Requiring any more interaction increases the mental taxation resultant from using the library.

1.2.4 Data.Array.Accelerate

Data.Array.Accelerate is a Haskell project[11], and accompanying library[12], providing massive parallelism to idiomatic Haskell code. It aims to approach the performance of ‘raw’ CUDA implementations, that utilise handwritten kernels.

The library introduces new types for compute containers. Built-in types are wrapped prior to inclusion in any computation. This allows the run-time to gather information about which datasets need to be transferred to compute-devices, and how to structure them in device memory.

It has received some significant optimisations[13] that target the inefficiencies present when an unnecessarily large number of kernels would be generated and executed, due to the composition of functions.

Divergences A disadvantage of relying on `Data.Array.Accelerate` for general-purpose computation is the relative difficulty often associated with becoming a competent Haskell programmer. The language diverges greatly from many mainstream languages. It requires programmers to state calculations in purely functional form.

The `Accelerate` library offers an easy transition into GPU programming for existing Haskell programmers. However, people with little Haskell experience may struggle to construct valid code.

To counter this, a more forgiving non-purely-functional language will be chosen for this project. Using a language that is easy for beginners to pick up will allow more people to attempt parallelising execution of their calculations.

1.3 Synopsis

1.3.1 Recap of motivations for research

- Improvements in sequential execution performance are lacking, thus a switch to parallelism is necessary.
- There is a lack of software developers who are sufficiently experienced with parallel programming.
- Without parallel execution of code, a large portion of the potential throughput present in a modern system is wasted.
- Easing the parallelisation of primitives will let novice developers achieve greater device utilisation.

1.3.2 Brief description of proposed solution

The proposed solution is a plug-in library that allows certain standard-library functions to be executed in parallel, automatically, without complicating the calling code. This will allow investigation into the advantages of algorithmically distributing computation over multiple compute-units.

With the project's deliverable remaining as similar as possible to standard-library code, and requiring no prior knowledge of parallel program construction, novice users will be able to benefit from any increased throughput.

The produced library should be assessed on ease-of-use and performance. Clearly demonstrating the benefits of the library will allow developers to recognise if and when its inclusion would be beneficial to a personal project.

Chapter 2

Overview

2.1 Project Aims

2.1.1 Improving the performance of dynamic languages when executing data-driven tasks

Dynamic, interpreted languages are commonly celebrated for their increased succinctness over static, compiled languages. Often, they greatly reduce the amount of code that is necessary to perform common tasks. However, they continue to be overshadowed by the throughput resultant from heavily optimised compilation of static languages, particularly for performance-intensive procedures. A typical performance divergence is shown in Figure 2.1.

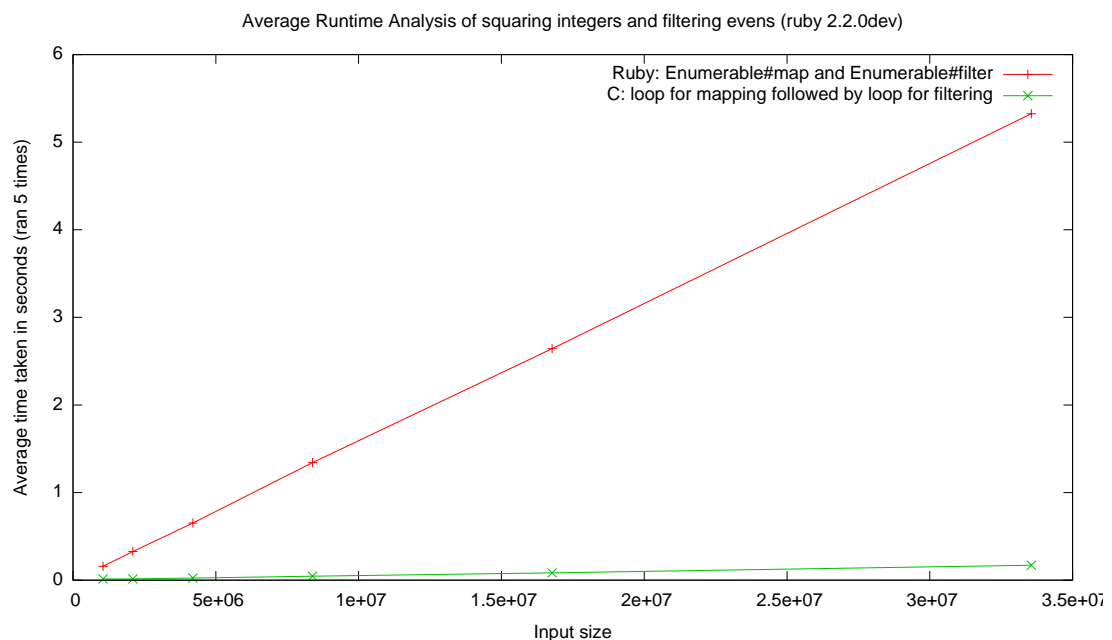


Figure 2.1: Graph demonstrating the significant difference in performance when operating on large datasets in C and Ruby.

RubiCL aims to investigate and mitigate any decreased performance experienced when using the Ruby language for data processing. By producing a more efficient implementation of computational tasks, users will be able to tackle larger scale problems without needing to learn new toolchains.

Indicators of success Progress towards this goal can be evaluated by comparing the performance of data-driven computation tasks in Ruby, with and without the library’s contributions, to that of functionality provided by native extensions written in static languages. Further success can be measured by investigating whether increased magnitude computation now terminates within reasonable time, due to the project’s contributions.

2.1.2 Facilitating a larger scale of experimentation in a REPL environment by non-expert users

An interactive environment, such as a Read-Evaluate-Print Loop (REPL), is commonly useful for rapid prototyping. It allows online processing of data without the need to produce all of the required code upfront, as shown in Listing 2.1. REPLs are absent from many languages. In supported languages, they allow the user to continuously query data and return intermediate results. Often, a quick turnaround between idea and response leads to more questions. This can enable an investigational attitude to computer programming.

Listing 2.1: A basic example of using a REPL environment for data analysis.

```
1 dataset_1.mean
# => NoMethodError: undefined method `mean' for Array

module Enumerable
5   define_method(:mean) { map(&:to_f).inject(&:+) / size }
end
#=> :mean

9 dataset_1.mean
#=> 23.6

dataset_2.mean
13 #=> 23.2
```

By widening the scope of problems that can be evaluated within a REPL, RubiCL shall enable a larger scale of investigation. Analysis of particularly large datasets is currently unavailable to novice users, due to the amount of computation required.

Indicators of success The completed library should be presented to novice analysts, users with mathematical insight but insignificant programming prowess. If they are able to easily answer queries about large datasets, the system’s design will be judged as successful. As with the previous goal’s evaluation, response time within a REPL environment will be examined.

2.1.3 Exploring the extensibility of the Ruby programming language

Ruby has served as a suitable foundation for many Domain-Specific Languages (DSLs), including build tools[14] and web frameworks[15].

The language has open classes, whereby the structure of object classes can always be altered at run-time, even after definition ends. It also permits a variety of meta-programming techniques, allowing complicated code to appear misleadingly simple at the surface.

Listing 2.2: The Sinatra DSL for simple web programming hides complexity when writing basic web services.

```
require 'sinatra'

3 get '/hi' do
  "Hello World!"
end
```

Objects in Ruby are often regarded as *duck-typed*. This means that the system should care only about how an object behaves — “If it looks like a duck, swims like a duck, and quacks like a duck, then it probably is a duck.”[16]

Since function invocation uses a *method-sending* approach, the underlying implementation can be altered significantly as long as an expected dialog is presented to the run-time.

This project demonstrates integrating drastically different processing techniques into the language’s run-time. It achieves this without greatly affecting the code that a user must write in order to use them.

Indicators of success The integration will be successful if the interface for processing data remains consistent. Parallelism should be implicit and not requiring direction from the programmer. Again, user testing will evaluate this.

2.1.4 Effective code generation and reuse on the OpenCL platform

OpenCL can provide high throughput computation, often utilised by bespoke systems such as cryptographic hashers and video encoders. However, there is a significant amount of configuration and set-up code associated with each parallel tasks performed. Code reuse is difficult to achieve on the OpenCL platform due to the specificity of kernel execution.

Without techniques for reuse, advances made by one parallel project may not be applicable to others. In this case, programmers writing parallel systems must implement all subtasks from the bottom up when constructing the full solution. As it is hard to incorporate the partial solutions of others, barriers to entry are further increased.

This project undertaken will attempt to recycle the partial solutions of primitives as much as possible. This allows investigation into how much reuse is possible, given an ideal system with a single author.

With greater code reuse, optimisations of a given subtask will improve all primitives utilising the component. This directs experimentation when searching for performance improvements.

Indicators of success Unfortunately, code reuse is often best measured subjectively. Yet, the developer's opinion when reflecting on the development experience may provide useful insight. If code reuse techniques facilitate the development of this particular OpenCL project, it is likely that they may be beneficial to developers elsewhere.

2.1.5 Applicability to a variety of platforms, avoiding over-tailoring for a specific machine

The project should be packaged in a manner that facilitates installation onto a new, supported, system. In addition, it should achieve performance enhancement without having to be adjusted significantly by the user.

As a result, no assumptions about the specific hardware present can be made, apart from full OpenCL support. This will allow the project to support a range of current and future compute-devices.

Indicators of success Deployment of the system to new hardware will be attempted, after the development phase has concluded. If the system remains performant and the deployment procedure does not require change, this is evidence of sufficient hardware agnosticism.

2.2 Leveraged Software Components

The project will provide its functionality to users through the utilisation of two previous bodies of software: The OpenCL library and the Ruby programming language.

2.2.1 OpenCL

The project requires interaction with heterogeneous processing devices present within a user's system. It achieves this via the hardware vendor's implementation of the OpenCL library.

OpenCL is an open framework for executing tasks, described by C99-syntax *kernels*, on a variety of devices. Suitable targets include multi-core CPUs, APUs, and GPU from the majority of commodity hardware vendors.

The Khronos Group maintains and frequently updates the OpenCL standard[17]. Participating vendors include Advanced Micro Devices (AMD), Apple, Intel, and NVIDIA. However, the quality and accessibility of implementations varies greatly.

A stated goal of the OpenCL project is to "allow cross-platform parallel programming". The underlying processing devices present on a system are abstracted, allowing code to be written without explicit knowledge of target architectures. This theoretically enables developers to write applications for a personal system and then later scale execution to a massively parallel workstation, without significant code modification.

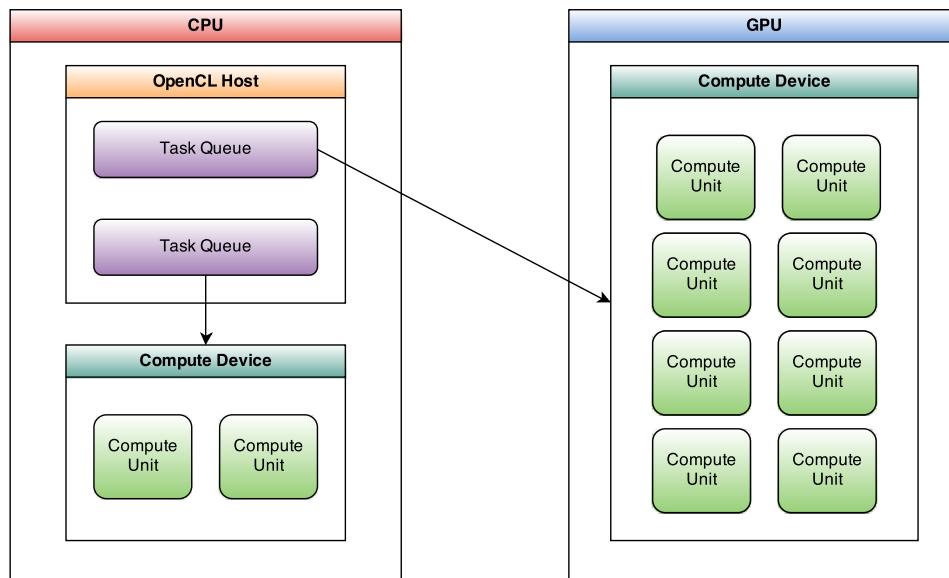


Figure 2.2: The OpenCL architecture model.

Architecture model As Figure 2.2 illustrates, the architecture model presented by OpenCL is as follows:

Host device The system's CPU. It interacts with the execution environment and is responsible for discovering and selecting compute-devices present on the system. The host device initialises one or more *contexts*, whereby any devices within a single context have access to shared task and memory buffers.

Compute-devices The system's available processing devices, capable of scheduling OpenCL kernel work-groups. Before enumerating compute-devices, the available *platforms* must be discovered by the run-time. Usually, there is a platform presented for each unique OpenCL supporting vendor with hardware installed. Devices are then retrieved on a per-platform basis, either filtered by type (CPU/GPU) or not.

Compute-units Discrete units of hardware present within a processing devices, capable of scheduling and executing OpenCL kernel instances. Kernel execution occurs across internal *processing units*, such as Arithmetic Logic Units (ALUs).

Execution Model OpenCL has a simple execution model, allowing both *coarse-grained* and *fine-grained* parallelism. Programmers write parallel code from the reference frame of a single kernel execution. Each instance orients itself only through access to its *local* and *global* id, expanded on shortly. Larger calculations are a direct result of cooperating kernel instances.

Kernel instances, scheduled for execution on compute-devices, are referred to as *work-items*.

The OpenCL standard calls a collection of work-items a *work-group*. Work-groups are the unit of work dispatched to a device. The number of work-items within a group is set by the programmer,

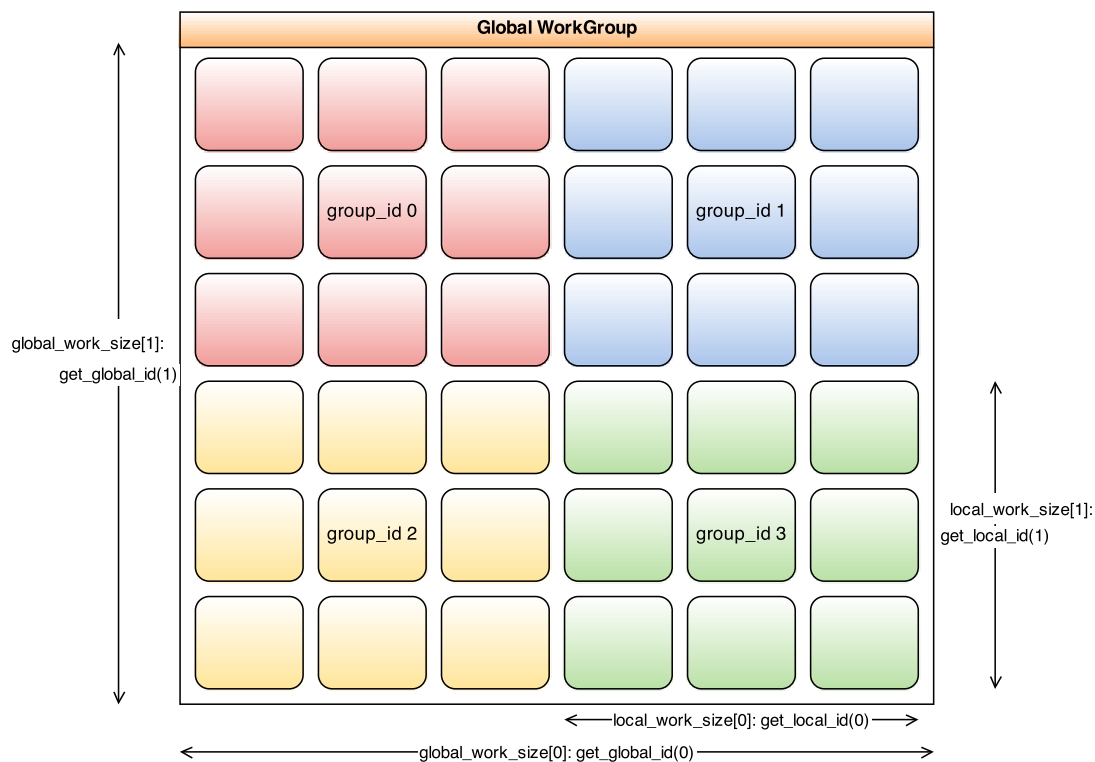


Figure 2.3: The OpenCL execution model.

providing the `global_work_size` parameter. Each kernel invocation is enumerated with a global `id`.

In addition to flat enumeration, the computation can benefit from the abstraction of work *dimensions*. For example, a calculation over 100 elements can be represented as a 2-dimensional 10×10 calculation. When utilising dimensional abstraction, access to either unique global `id` or x, y offsets is available.

Higher dimensions are available for further structuring of tasks. The spatial abstraction provided is particularly useful when there is topological significance to the processed data. In these circumstances, the `local_work_size` parameter provides further benefits.

When `local_work_size` is specified, again possibly with dimensionality, the work-items are additionally divided into subgroups. Memory allocation can use the `__local` qualifier. In this case, data will reside in higher-bandwidth buffers that can only be synchronised between members of the same local work-group. With the addition of this second, local tier of memory, the OpenCL model hints at how efficient kernels should be constructed. Being aware of the positioning of data and its dependencies is key when developing efficient kernels, free of memory-synchronisation bottlenecks.

Much of the project's implementation effort concerning OpenCL will be mapping data required by common algorithms to efficient arrangements within device memory. This mirrors OpenCL development in general. The fact that this task is so laborious is a reason why heterogeneous parallel programming on the OpenCL platform is still under-utilised in the wild.

Comparison with CUDA OpenCL is not the only available computation framework for interacting with GPU devices. As mentioned earlier, a competing technology is NVIDIA's CUDA.

During the planning phase, RubiCL considered both choices. Ultimately, the decision was made to use OpenCL over CUDA for several major reasons:

Multiple vendor support CUDA is not an open standard. Its parallelism framework is only available on NVIDIA hardware. Using a library supported only by a single vendor to provide the project's hardware interfacing would lead to far fewer systems being able to benefit from accelerated processing.

CPU and GPU execution By using OpenCL, RubiCL will be able to execute kernels on both CPU and GPU devices. This contrasts the GPU-only focus of CUDA. This greatly increases development convenience. Development can occur on a mobile laptop, functionally tested with its CPU. Afterwards, the library can be transferred to desktop workstations for performance testing on a variety of hardware.

In addition, this opens up the possibility of attempting code execution on both devices concurrently. This will investigate whether complete system-wide utilisation is beneficial for a single computation.

Disadvantages of choosing OpenCL There are several downsides to using OpenCL instead of CUDA. The programming model is generally agreed to be less developer friendly. This is perhaps due to the need to include far more abstraction over the range of target devices. In addition, due to the need for compatibility with several device families, OpenCL can be less performant out-of-the-box than CUDA. Advanced knowledge of how to tweak device-specific parameters to avoid execution bottlenecks can help avoid this.

Current state of OpenCL implementations A final major disadvantage of OpenCL at the moment, is the current quality of some vendor implementations. All vendors advertise themselves as being OpenCL-compatible when marketing their hardware. However, in reality it is often harder than advertised to achieve a working system.

For example, NVIDIA have made no attempt to hide the fact that they would much rather everybody used CUDA instead. At the time that this report was written, they were sufficiently slow enough at releasing libraries as to be a full version of the OpenCL specification behind other vendors. Features that are supported also perform much worse than expected.

Intel are up-to-date with library implementations but only have full non-Windows support if you have purchased non-consumer grade *Xeon* processors.

Hopefully these issues will be rectified if OpenCL continues to gain traction in the future. As a short term response, the RubiCL project has been implemented on well-supported hardware only: An Apple *Macbook Air* containing an Intel *Haswell* APU, and a desktop system containing an AMD CPU and GPU.

Apple and AMD both have high-quality OpenCL 1.2 libraries and seem to be the two companies most invested in increased OpenCL uptake. Apple have recently started encouraging desktop

software developers to schedule suitable tasks on the GPU via OS X's Grand Central Dispatch (GCD).

2.2.2 Ruby

Language features Ruby[18] is an interpreted, dynamic language, embracing a variety of programming paradigms. It contains many features designed to increase its extensibility via meta-programming.

Execution centres around the creation of objects, all data inherits from at least `BasicObject`. Function invocation is triggered by sending the target object a *message*.

Upon receipt of a message, it is handled by the lowest level of an object's inheritance-hierarchy — the composed chain of class and module extensions that are mixed-into the object instance. A level will either respond to the message or, if unable to, propagate the request further up the chain.

A common meta-programming technique is to redefine how a module within the hierarchy responds when a method definition is missing. Instead of simply passing the message to the next level, it can inspect the name and arguments of the function, or its own state, and give a response. This cancels further progression of the request.

This flexibility is often used (or abused) to reduce the amount of boilerplate code written.

In addition to dynamically responding to received methods, objects are often substituted for objects of another class that have subtly different behaviour. This will be successful as long as they respond the same method calls. Therefore, it is common practice to consider only the interface presented by interacting objects and not their individual types.

The benefit of this *duck-testing* is that the same series of method requests, present in a line of code, can cause very different patterns of computation. If the response of a single link in the chain is altered, the programmer would be unaware, and unconcerned, as long as the expected pipeline result is returned.

This technique of redirecting computation will be explored by the RubiCL library. It allows a decoupling of the programmer's requests and the underlying, massively-parallel implementation.

Native extensions The latest versions of the Ruby language make it simple to produce native extensions. Functionality is provided by C shared-objects that interact with the underlying Ruby Virtual Machine (RubyVM).

Listing 2.3: The C code defining a module with the ability to perform native actions.

```

#include "ruby.h"
#include "something_native.h"

3
/* All Ruby objects are of type VALUE and must be unboxed */
/* Every method takes self as an explicit argument */
VALUE
7 methodSomethingNative(VALUE self, VALUE int_param_object) {
    int param = FIX2INT(int_param_object);
    int result = doSomethingNative(param);
}

```

```

11     return INT2FIX(result);
    }

    void /* module_example is name defined in Makefile */
15 Init_module_example() {
    VALUE ModuleEx = rb_define_module("ModuleExample");
    /* Visibility, Module, Name, Method, Arg count. */
    rb_define_private_method(
19     ModuleEx, "something_native",
        methodSomethingNative, 1);
    }

```

Adding native methods is as simple as performing the heavy-lifting as one would in a pure C application. The RubyVM library then allows the programmer to create a Ruby module or class with mappings between method names and the underlying implementations.

Listing 2.4: A Ruby class utilising a native extension module.

```

require './module_example'

3 class NativeThing
    include ModuleExample

    def method_requiring_native
7     something_native(1)
    end
end

```

The required complication of converting between Ruby objects and basic C types is handled via macros, defined for all sensible conversions.

Once an extension has been compiled, the shared-object file is required and the constructed object is available, no differently to a pure Ruby implementation. In the case of RubiCL, modules for particular concerns are provided and then mixed-into classes that require native functionality.

Suitability as the project’s target language The project decided to use Ruby as the target language as, alongside Python, it is often recommended to beginners for analytics and *data-science*. This is perhaps due to the syntax being relatively straightforward and often self-documenting.

Unlike Python, Ruby’s design is less opinionated about the *principle of least surprise*, and therefore makes it much easier to drastically extend its capability while hiding complexity from unaware users.

In addition, the need for constant method-hierarchy lookup has been blamed for its poor performance. The potential for dynamic redefinition of methods complicates caching and can heavily impact certain compute-intensive tasks. This makes Ruby a suitable target for a project aiming to offer an optimised library for such tasks.

2.3 Project Progression

2.3.1 Timeline

Initial focus In the project's first year, most of the time was spent researching existing parallel frameworks. The project's initial goal was to present a *MapReduce* run-time. Therefore, systems like Phoenix++[19] and StreamMR[20] were evaluated.

Part-way through the year, during prototyping, it became clear that there are several disadvantages to producing (yet-another) *MapReduce* system:

- The run-time resource management is overkill on a singular, massively parallel machine. When isolated failure is unlikely, more lightweight processing paradigms can be used with greater efficiency.
- Previous projects have hit issues caused by GPU architecture. For example, tasks that emit tuples must be run twice: Once to count the number of tuples emitted, and again to actually produce the results. This is needed as OpenCL kernels do not allow dynamic allocation of memory.
- Since OpenCL compute-devices execute only kernels, there are just two options for task specification:

Firstly, users can specify tasks in OpenCL kernel form. This is terrible for system usability. Products such as *Hadoop* are successful due to features such as the *streaming API*, allowing code to be written in familiar languages when performing parallel tasks on tuple streams.

Secondly, the system could translate an existing language into OpenCL kernels. This would allow users to stay within their comfort zone, yet still utilise the parallel architecture of many modern systems. Unfortunately, this task is an enormous undertaking. Recently, progress has been made on generating CUDA executables from LLVM Intermediate Representation (IR). Similar breakthroughs for the OpenCL platform are lacking.

Moving away from MapReduce There are clear benefits of utilising familiar languages when orchestrating parallel tasks, such as significant increases in usability. Yet, it is currently infeasible to translate the entirety of stated programs. With this in mind, the decision was made to lower the scope of direction, with the user stating only parallel subroutines and having OpenCL dispatch of said subroutines automated.

At the close of the first year, a prototype system was produced that allowed a user to perform map and filter tasks. Specification of tasks was provided by a string of C expressions that would be interpolated into stock kernels.

Listing 2.5: Example of prototype system workflow.

```

DataSet.create(
  name: :one_to_ten,
  type: :int,
  data: (1..10).to_a
)
```

```

7 FP::Map.create(
  name: :add_one,
  key: [:int, :i],
  function: 'i += 1;'
11 )

FP::Filter.create(
  name: :add_three_is_even,
15 key: [:int, :i],
  function: 'i += 3;',
  test: 'i % 2 == 0'
)
19

DEVICE = OCLDevice::CPU.get

DEVICE
23 .load(:one_to_ten)
  .fp_map(:add_one).fp_filter(:add_three_is_even)
  .output
#=> [3, 5, 7, 9, 11]

```

This proof-of-concept demonstrated that performance gains were achievable by performing computation outside the confines of the RubyVM.

However, evaluation of the prototype highlighted several flaws:

- Using the library was incredibly verbose. Creating named objects to represent each state of computation meant that a line of pure Ruby code could spawn tens of lines of library code when converted to parallel execution.
- Lots of redundant parameters were required by the system. There is no reason for a map task to specify its input parameter type when the syntax can be checked by a compiler. The separate declaration and usage of element variables increased the potential for bugs, in addition to exposing implementation details to the user.
- A lack of task optimisation causing higher-than-necessary workloads. Two consecutive map tasks would require two passes over the data instead of just one, as the intermediate result was produced despite remaining unused.
- Code quality was poor. This was mainly due to the combination of venturing into a previously unexperienced programming paradigm, and organic growth of functionality during rapid prototyping.

Producing a prototype with full functionality is useful to discover the requirements of a system. It is then much easier to redesign a new system, one that is much more elegant yet achieves the same results.

Learning from mistakes The system's redesign at the start of the second year specifically targeted previously identified flaws:

- First-class function support allows the library's interface to mirror standard higher-order func-

tion usage. Since anonymous function are used, this removes the verbosity of creating many named objects.

- Some parameters are no-longer required, or inferred, due to a change in internal design. For example, anonymous functions document the input parameter throughout the calculation, so specifying this separately is unnecessary.

Another example is subroutine type information. The computation pipeline can now keep track of the buffer type at any given point in execution. This can be used to guide kernel creation, instead of requiring user-submitted type definition.

- By deferring and combining tasks, as documented in the *Design* chapter, unnecessary computation can be avoided.
- The system architecture was redesigned, with a focus on testing and ease-of-modification. This helps maintain the software quality of the replacement system, even as requirements shift.

2.3.2 Difficulties

Several unforeseen issues have slowed down progress in certain stages of the project's progression.

Initial development system The target GPU test-bed was originally a desktop system containing a NVIDIA GTX 670 GPU. It also contained an Intel Haswell APU. Unfortunately, it became clear during the process of porting the codebase, initially developed solely on a laptop, that the state of the required libraries was much worse than advertised.

Had the libraries for the system been available, the produced framework would allow task scheduling on either compute-device within the APU, or the GPU.

The difficulties encountered were as follows:

- Intel's OpenCL implementation only allows access to the graphics-processing APU co-processor under two conditions: If the operating system is Windows 7/8, or if the device is a Xeon processor. Xeon devices are not present in affordable desktop systems. The owned test-system did not support the required socket-style.
- Development in Windows was not possible due to the need to build several system components. The latest Ruby language snapshot and the extension modules necessary for the library to operate must be built, from source, during development. This process is still bug-ridden on non-*NIX systems.

Following these setbacks, the goal of utilising the APU's graphic subsystem in addition to the CPU was abandoned. GNU/Linux was installed on the desktop system. However, the situation was further hindered when it became clear that the capabilities of NVIDIA's OpenCL implementation were vastly overstated. With no support for OpenCL 1.2 and suboptimal performance using 1.1, the high-end GPU present would not provide as much of a performance boost as initially anticipated.

Replacement system In order to continue the project's goal of properly exploring the potential benefits of GPU programming, the decision was made to purchase an 'ideal' hardware platform to continue development on.

The system, consisting of an AMD *FX-4130* CPU and an AMD *R7 260X* GPU, was ordered and assembled after the initial problems were encountered. This caused a slight stall in development. However, it was estimated that with hardware utilising a single, AMD OpenCL implementation, productivity would be vastly increased. Luckily, this replacement system was successful enough to make the delay worth experiencing.

2.4 Completed Work

The produced deliverable is a library for outsourcing computation on homogenous datasets to the CPU or GPU. The complete list of functionality provided is documented in the *Software Architecture* section of the *Design* chapter.

As a basic metric of the amount of work involved, the size of the produced codebase is follows (as reported by `cloc`):

Management system 31 Ruby files, each implementing a single class or module, with a total of 1571 Lines of Code (LoC).

Back-end library 3 C files, providing the ability, given a suitable kernel, to dispatch all implemented parallel tasks on hardware devices via the OpenCL library, a total of 1226 LoC.

Native extension 1 C file, containing 563 LoC, enabling the Ruby run-time to perform parallel tasks by orchestrating the use of primitives defined in the back-end. Also contains a 16 LoC Ruby file that generates the 201 LoC `Makefile` needed to build the project.

Test suite 19 Ruby files, written using the RSpec library, ensuring system correctness by performing a comprehensive set of tests. 566 LoC in total.

Chapter 3

Design

3.1 System architecture

3.1.1 Interface

The produced system is able to interact seamlessly with existing Ruby code, via type annotation on collection objects.

Listing 3.1: Redirecting a computation through the RubiCL library via type annotation.

```
# Sequential stdlib code
2 (1..1_000_000)
  .map { |x| x + 15 }
  .select { |y| y % 15 == 0 }

6 # Parallel code using RubiCL
  (1..1_000_000)[Int]
  .map { |x| x + 15 }
  .select { |y| y % 15 == 0 }[Fixnum]
```

When a user is sure that all objects within an `Enumerable` are of a single, basic type, they can append a type declaration to the container. This declaration lies within the method pipeline and states the equivalent C type. The object is then wrapped by the RubiCL execution environment.

Further method calls are swallowed by the `Device` instance handling the dataset, and pushed onto a work-queue.

Eventually, a result is requested. This occurs either by a user casting back to a Ruby object class, or by performing a terminal action such as summation. The work-queue is then optimised and mapped to OpenCL kernels, dispatched to the target compute-device.

The produced wrapper solution for including additional functionality to the Ruby run-time is ideal for maintaining usability. Programmers must grasp only the concept of annotating type-conversion at the beginning and end of any calculation pipeline. All other syntax of the library is identical to normally-written Ruby code.

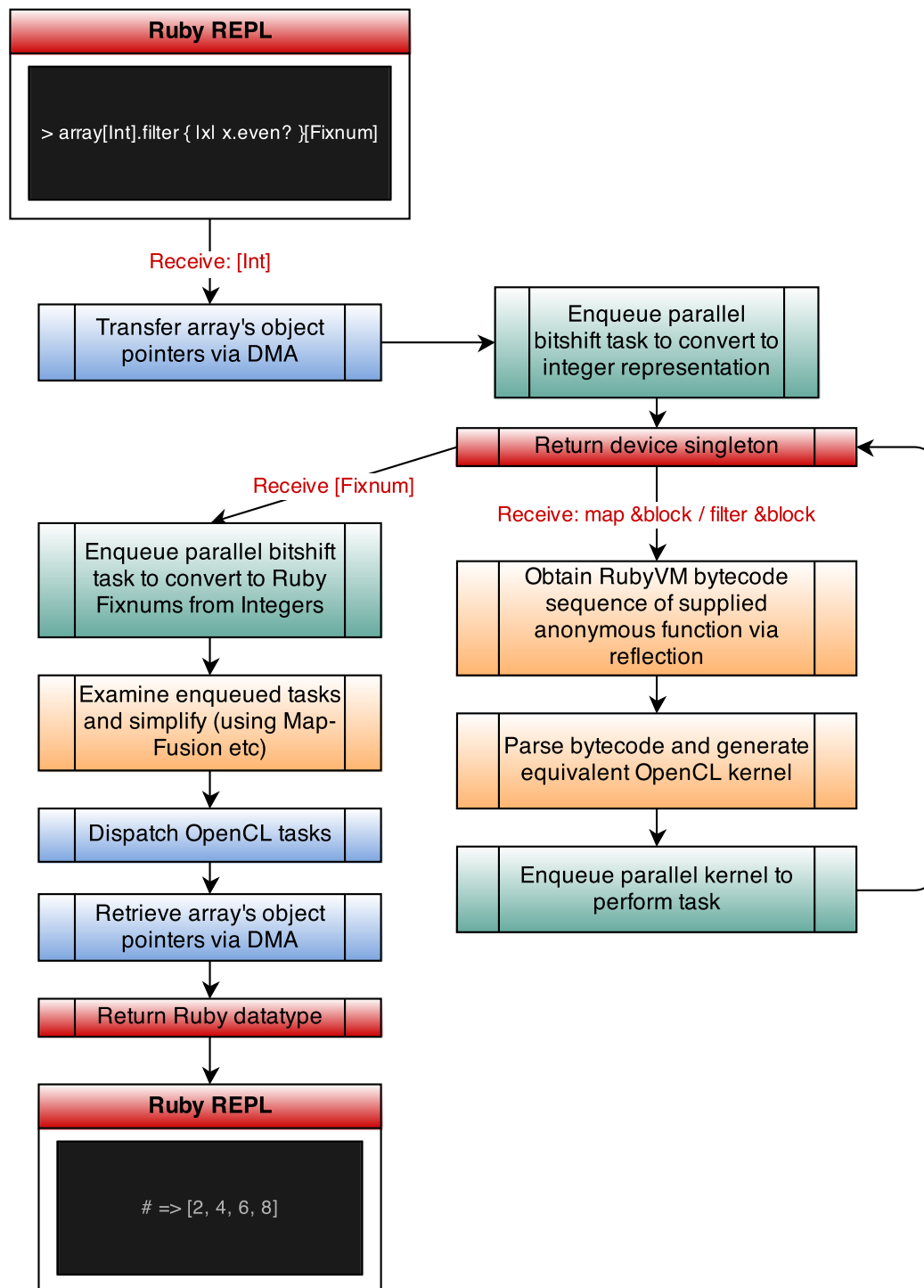


Figure 3.1: RubiCL execution model.

Despite the simplicity of the library's presented interface, there is a lot of work going on behind the scenes. The technical details of which will be discussed over the following 2 chapters.

As an overview, the steps undertaken by the RubiCL library for the example given in Figure 3.1 include:

- Moving the dataset elements into continuous memory, addressable by the compute-device.
- Recording the loaded dataset type, to allow static type-system operations.
- Parsing the `block` argument of the `#map` task's bytecode and constructing an equivalent C99 expression.
- Parsing the `block` argument of the `#select` task's bytecode and constructing an equivalent C99 expression.
- Inserting a `Map` task at the beginning of the `TaskQueue` to convert from Ruby objects to C ints.
- Inserting a `Map` task at the end of the `TaskQueue` to convert from C ints back to Ruby objects.
- Simplifying the 4 tasks in the `TaskQueue` to a single, `MapFilter` task via *fusion*.
- Generating the OpenCL kernel required to perform the `MapFilter` task.
- Executing the produced kernel on the compute-device, recording metrics.
- Releasing resources acquired by the OpenCL library during the task.
- Returning the resultant values as a Ruby array.

3.1.2 Software architecture

The library is constructed from the following set of modules and classes, alongside their responsibilities:

RubiCL Environment singleton and top level namespace. The library's functionality is included in an application by requiring this module. It handles the import of all sub-components of the run-time. Other responsibilities include storing versioning metadata and selecting which available device should be the default compute target.

Interface:

self.opencl_device Returns the current compute-device. (The default for this value is `RubiCL::CPU`)

self.opencl_device=(Device) Sets the current compute-device.

CastAccess A module designed to extend container types, providing the ability to initiate a computation pipeline. For example, the Behaviour of the `Array` built-in class is extended by mixing-in this module in the following manner:

```
Array.class_eval { include RubiCL::CastAccess }
```

This allows parallel primitives performed on Arrays to be executed by the compute-device following an annotation, such as `[1, 2, 3][Int]`. Upon casting, the actual conversion operations performed are specified by the target class. This module is decoupled from implementation and provides purely syntactic enhancements.

Traditionally in Ruby, invoking the `[]` method of an `Enumerable` is only used for indexed access to collection members. The standard implementation supports receiving integer arguments and returns the element at the given offset. It also supports Range arguments and returns the corresponding continuous subset.

The assumption was made that that providing a `Class` constant as an argument here is something that would never occur in common use. Therefore, the RubiCL library uses occurrences of this calling behaviour to indicate that a dataset should be wrapped.

Interface:

[] (Type) Overridden on extended object to call the conversion method, provided by a `Class` argument's `rubicl_conversion`, on the current compute-device, referencing the dataset it was called on. Behaviour when called with a non-`Class` argument is unchanged.

Target C-type classes An observant reader may notice that the constant `Int` is passed in Figure 3.1 when signalling that the container should be transformed into C type ints. This class is not defined within the standard library, instead `Fixnum` is the container for fixed-precision integers that can be encoded within a single machine word.

The `Int` class was constructed to represent the abstract type of C integers. In addition, the `Double` type has been defined for double precision floating-point numbers.

Each C-type class defines how to transfer a similarly typed input dataset to the compute-device, via methods defined by the `BufferManager`.

Interface:

self.rubicl_conversion Provides the method and type arguments to call on the current compute-device, alongside a dataset, in order to load it.

Native Ruby result classes At the end of the computation pipeline, results are retrieved either by casting back to a Ruby type, or by performing a terminal action such as summation.

The Ruby classes used to convert back to the calculation's result type are provided with the standard Ruby implementation: `Fixnum` and `Float`.

Mirroring the responsibilities of the C-type classes, additional static methods have been added to these classes to instruct the `BufferManager` how to return a result dataset for the given type.

Interface:

self.rubicl_conversion Provides the method to call on the current compute-device, in order to retrieve the typed dataset.

BufferManager In order to prevent the Device class from becoming a *god object*, manipulating the device buffer is performed through a service object. The BufferManager provides an interface to load objects, specifying their C-type, and later retrieve them. The type of the currently loaded buffer is then stored, to assist kernel generation for queued parallel tasks.

The manager also provides caching of the dataset to prevent unnecessary hardware retrieval if no operations have been performed.

The manager's necessary ability to interact with an OpenCL buffer is provided by the BufferBackend native extension module.

Interface:

load(type: Type, object: Object) Makes the provided object addressable by the OpenCL compute-device.

retrieve(type: Type) Retrieves the resultant object from the compute-device address space.

access(type: Type) Returns a handle to the device address space, to be passed by Device when executing tasks.

Device An abstract superclass, providing all functionality of the execution context during a method pipeline. Instantiated as a singleton, in either GPU or CPU flavour. The subclass overrides only the initialisation procedure, passing the correct device-type flags to the OpenCL API, and provides a means to later differentiate between device types. Knowing what type of hardware device a kernel will execute on allows specific optimisations, such as avoiding *bank conflicts* for Scan tasks occurring on a GPU.

Interface: Where possible, all methods return the device context to allow method chaining.

▯(Type) Used to signal the end of a computation pipeline. Sends the method provided by `Type.rubicl_conversion` to itself.

load_object(Type, Object) Delegates to the buffer manager.

retrieve_integers Delegates to the buffer manager.

retrieve_doubles Delegates to the buffer manager.

sort Enqueues a task to sort the buffer.

zip(Enumerable) Flushes the current pipeline, then creates a tuple buffer from the result and the inputted Enumerable.

fsts Bifurcates a loaded tuple buffer, keeping only the first elements.

snds Like the previous method, but keeps only the second elements.

braid(&Block) Collapses a buffer containing a list of tuples into a list of single values, using the provided combination function.

map(&Block) Mutates all elements within the buffer using the provided function.

filter(&Block) Rejects elements from the buffer that do not pass the provided predicate function. Aliased also as `select` to be consistent with the Ruby standard library.

scan(Style, Operator) Produces an array of intermediate results, equivalent to traversing the array and applying the reduction operator up until each point. Inclusive or exclusive option set via parameter, inclusive by default.

sum Returns the summation of all values in the buffer.

count(Value?, &Block?) If provided with a value, returns the number of times that the given value appears in the buffer. If provided with an anonymous function, returns the number of values in the buffer that satisfy the predicate. If no arguments are provided, returns the length of the buffer.

LambdaBytecodeParser Receives an anonymous Ruby function during instantiation and returns a set of equivalent C expressions on demand. The details of this procedure will be explained in the *Implementation* chapter. This translation stage enables the library to operate when the user states a problem in standard Ruby syntax only.

Interface:

to_infix Returns the function supplied to the constructor in infix form, using C syntax.

Logger A singleton used to log key actions to the terminal or disk, facilitating debugging. The current log level set determines whether output will be produced. Enables debug mode to be toggled in a single location.

Interface:

loud_mode Causes any logged actions to be displayed in the terminal.

quiet_mode Ensures logged actions do not appear in the terminal.

show_timing_info= Toggles whether segmented timing analysis appears before produced computation results.

TaskKernelGenerator Instantiated with a Task object, the TaskKernelGenerator assembles an OpenCL kernel performing the task. It handles the majority of OpenCL kernel boilerplate, with the task providing only specific computational operations.

Interface:

create_kernel Returns the kernel source for the given task.

Task An abstract superclass representing a stage within the computation pipeline. Subclassed with the specific type of operation. Provides tracking of variables required, computation statements and each task's unique name.

Interface:

descriptor A pretty-printed description of the task. Provides its name alongside a summary of actions performed.

to_kernel Returns the full OpenCL source of the task, obtained through the `TaskKernelGenerator`.

fuse!(Map) Present on `Map` tasks, allows a following `Map` task to be combined with the current task.

fuse!(Filter) Present on `Filter` tasks, allows a following `Filter` task to be combined with the current task.

pre_fuse!(Map) Present on `MapFilter` tasks, prepends the previous `Map` task's statements to the current task.

post_fuse!(Map) Present on `MapFilter` tasks, appends the following `Map` task's statements to the current task.

filter_fuse!(Filter) Present on `MapFilter` tasks, updates the filtering action to also require the following `Filter` task's predicate to be satisfied.

TaskQueue Stores the entire computation pipeline of the current execution chain. Enqueued tasks are appended to the queue. When a result is requested, the entire queue is optimised and then dispatched in as few tasks as possible. The rules for queue optimisation are discussed in the *Implementation* chapter.

Interface:

push(Task) Adds a `Task` onto the end of the queue.

shift Removes the first `Task` from the queue and returns it.

simplify! Compresses the `TaskQueue` by performing *fusion* optimisations.

Example interaction Figure 3.3 shows the interactions between classes during a typical parallelised computation.

3.1.3 Interacting with hardware devices

Interaction with hardware devices, present on the system, occurs via native extensions. These extension modules are mixed-into device singletons, created when the library is first launched. Figure 3.2 shows the functionality of these singletons and their subcomponents.

Both CPU and GPU objects, tasked with managing device state, inherit from a common `Device` superclass. The main difference in their implementation is differing initialisation procedure. Having two device types allows target-specific optimisation by the code generator.

The `Device` subclasses delegate maintaining the list of tasks to a `TaskQueue` object. In addition, they lack the ability to call memory management functions on devices. Instead of handling device memory directly, `Device` objects request functionality through an instance of `DeviceService::BufferManager`.

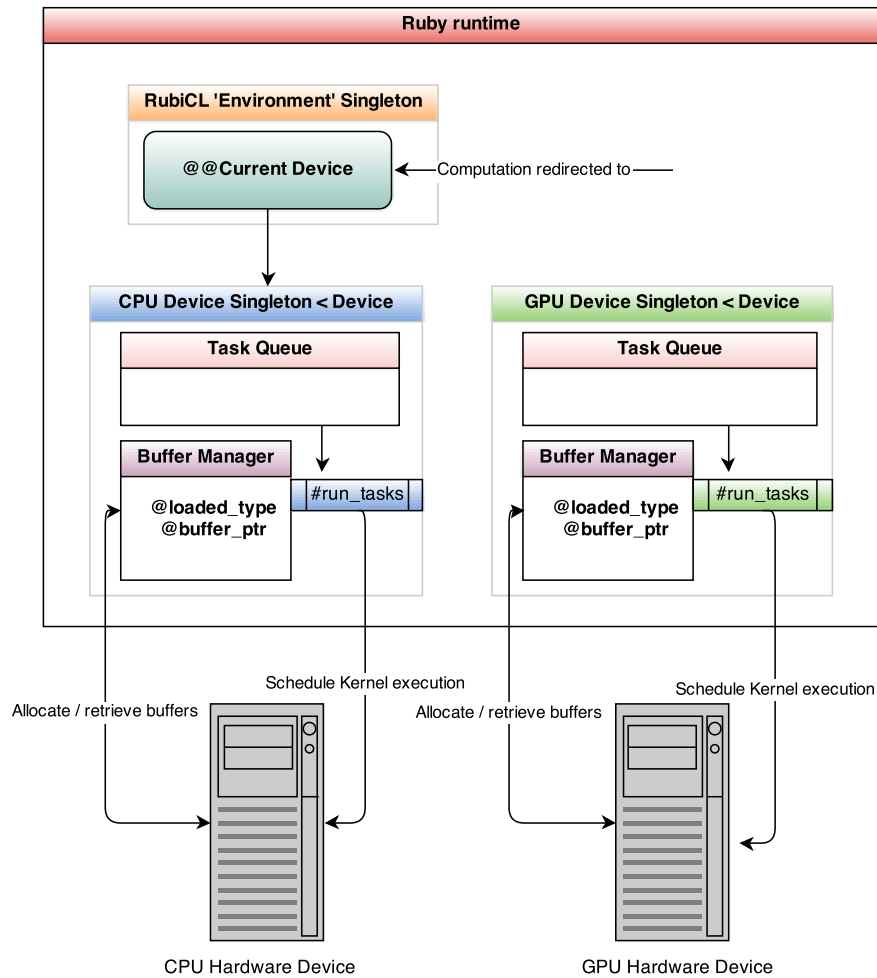


Figure 3.2: The RubiCL run-time maintains singletons for each device, used to trigger management functions and execute kernels.

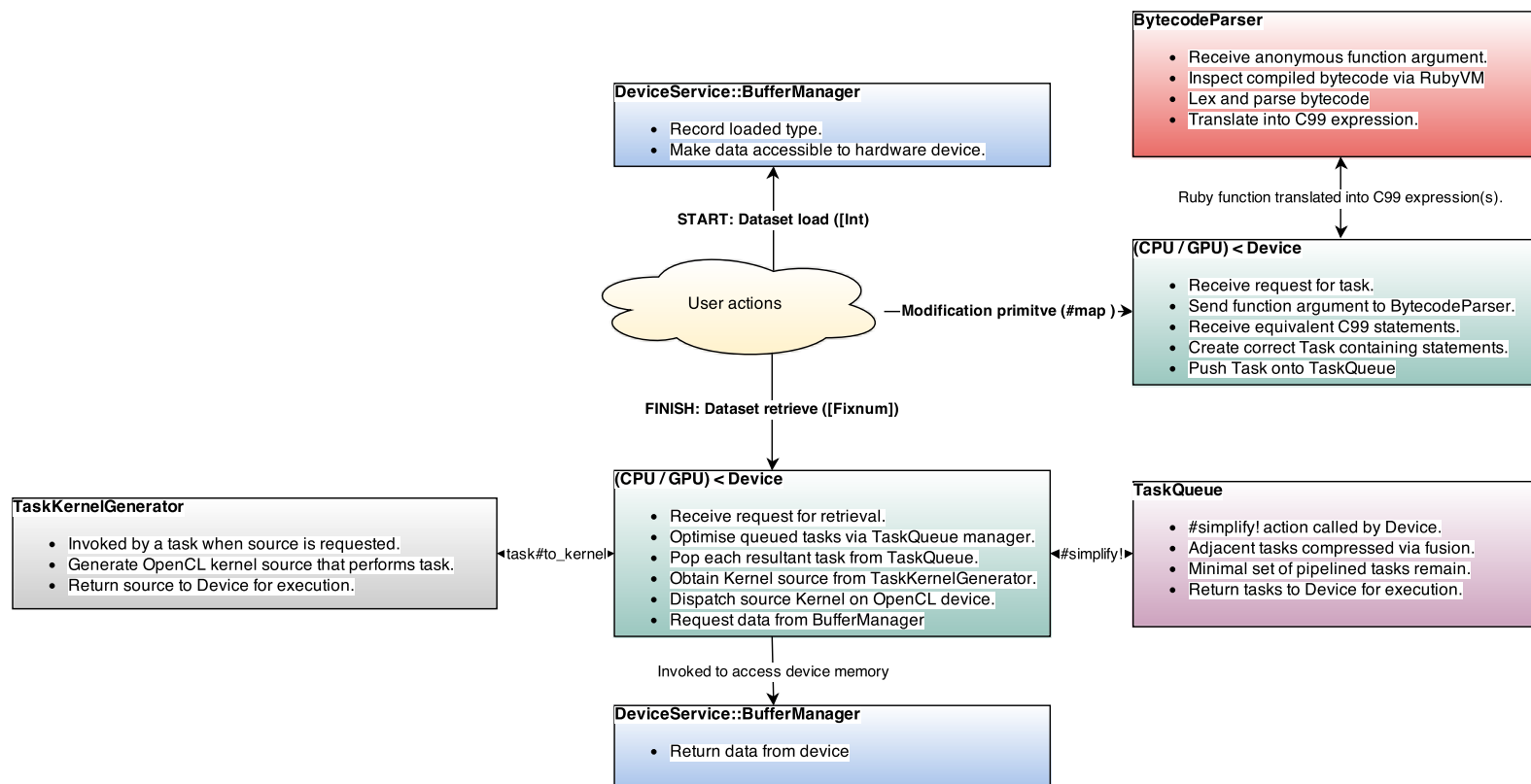


Figure 3.3: An overview of the interacting software components during the lifetime of a typical computation

Implementing all device logic that does not require hardware interoperability in Ruby made the system much easier to test. The time taken for the device control flow to execute is insignificant compared to the time taken for data processing. Writing this section in C would have been misguided as the performance benefits would not be worth the impaired rate of development.

3.2 Design choices

3.2.1 Type annotation

When parallelising computation using the RubiCL library, a dataset is initially ‘cast’ to the C-type equivalent. To signify the end of a computation it is finally ‘cast’ back to the Ruby type.

This method of redirecting a method chain using a wrapped object is intentionally similar to `Enumerable#lazy` in Ruby’s standard library.

`Enumerable#lazy` allows computation to be deferred until it is known how many results are needed. In some cases, such as the example presented in Figure 3.2, computation can be avoided when the results would be discarded.

Listing 3.2: Redirecting a computation through `Enumerable#lazy`.

```
def side_effect_increment(x, str)
  puts str
  x + 1
end

(1..5).map { |x| side_effect_increment x, "Non-lazy" }
  .take_while { |x| x < 4 }
# => [2, 3]

(1..5).lazy
  .map { |x| side_effect_increment x, "Lazy" }
  .take_while { |x| x < 4 }
  .to_a
# => [2, 3]

# Non-lazy invocation evaluates 'side_effect_increment' 5 times:
# >> Non-lazy
# >> Non-lazy
# >> Non-lazy
# >> Non-lazy
# >> Non-lazy
# Lazy invocation evaluates 'side_effect_increment' 3 times:
# >> Lazy
# >> Lazy
# >> Lazy
```

Keeping the usage akin to a conceptually similar feature should make the library easier for inexperienced programmers to get to grips with.

3.2.2 Eager or deferred task dispatching

During system design, the decision had to be made whether to eagerly evaluate parallel primitives or to buffer all requests and then dispatch tasks when a result is requested. This choice is not straightforward as there are benefits to either option.

Advantages of eager dispatch

- The kernel build and execution stages can be pipelined. For example, this allows the code generation and compilation stages to execute on the host CPU while the previous task is executing on the GPU.
- Compute device can easily be changed mid-chain. Although it will suffer a performance penalty due to the need to transfer the data buffer, having the buffer always in a consistent state allows a device well-suited in a particular primitive to pick up where another left off.
- Simplicity. No need to study equivalence rules.

Advantages of deferred pipeline

- Fewer resultant Tasks to schedule. Since adjacent combinable tasks are fused, there is less work done by the OpenCL compiler and work-group scheduler.
- Fewer accesses to global device memory. In the setup phase of each kernel, the elements to be transformed are loaded from the global device buffer into local storage. When multiple tasks are combined into one kernel, the intermediate result remains in unsynchronised memory until the task finalizes. This causes much less stress on the compute-device's memory subsystem.
- Fewer work-units scheduled. It is a waste of iterations to have 3 for-loops each modify a collection when all operations could occur in a single loop. It is similarly wasteful to execute N work-units 3 times when only N are needed.

The execution style chosen was to defer task requests and then execute optimised tasks when a result is required.

This mirrors the approach taken by many *Object-Relational Mappers*, such as ActiveRecord, combining a pipeline of queries into optimal SQL.

The assumption was made that requiring multiple passes over the input dataset was significantly more expensive than the one-off code generation tasks. This was verified by timing information collected during empirical testing.

3.2.3 Construction and processing of tuple datasets

In order to allow a greater variety of query styles to be accelerated, it became clear that tuples should be introduced as a data-type. This necessitated the development of functionality to load a dataset of tuple elements onto the compute-device. It also required supporting the execution of parallel queries, possible on standard datasets, on the new dataset type.

After careful consideration of the requirements, two methods of achieving tuple functionality appeared suitable for the project.

Custom structures of data for each element OpenCL supports the usage of structs in kernel code. With this in mind, it would be possible to store each tuple continuously in memory and use member access to retrieve each slot. The size of each tuple structure can be used to guide memory management on the host. There are both advantages and disadvantages to this method of implementation.

An advantage of using structures is the ease of supporting arbitrary length tuples. The host code only knows about the size of each tuple. This information is combined with the number of elements present when allocating the correct amount of device memory. The pre-compiled back-end code has no notion of tuple structure. Only the dynamically generated kernel code has the need to interact with slots within a tuple. As such, the structure handling code can be programmatically provided at the same point as task definition.

One disadvantage of using structures is the need to recreate the entire dataset whenever tuples alter in length. For example, if an array of 2-element tuples is loaded to the device, and a third slot is added to each, it is necessary to initialize a new buffer and fill it by copying existing values then inserting a new slot value for each tuple. This is the same issue faced when inserting an element within a fixed-size vector. This issue would result in an increased cost of the zip operator when creating or resizing tuples.

Virtual tuples stored in disjoint datasets When processing tuples of length 2, instead of creating a buffer storing tuples continuously in memory, two dataset buffers can be provided to each invoked kernel. The first buffer stores the first slot value for each tuple. Likewise, the second buffer stores all second slot values. The generated kernel code can then be designed to operate on tuples as intended, by accessing the indexed value from the buffer corresponding to the slot requested.

This method has the advantage that the creation and resizing of tuples is much less expensive. To create tuples, the second dataset, passed as a parameter to the zip operator, is simply provided to subsequent kernel invocations alongside the currently loaded buffer. When resizing tuples, the entire buffer does not need to be recreated because of a shift in individual tuple length. Instead, an extra buffer is passed to all scheduled kernels if the tuple has grown, or one buffer is released and is no longer shared if a slot has been removed.

While this method benefits from greater performance, it is more involved to implement arbitrary sized tuples compared to the previously suggested solution. The host code is now concerned with many disjoint buffers that must be managed and released after use, and all required slots must be provided as kernel arguments prior to scheduling of any execution. In short, the host code is far more coupled to the currently loaded dataset's contents than is desirable.

However, it is clear that the second solution, virtual tuples, achieves greater performance despite a more involved implementation. Therefore, it was chosen as the project's tuple implementation method. The initial implementation of tuples was limited to a 2 slot maximum so that the design could be completed quickly and verified as correct, but it is entirely possible to expand the system to support arbitrary length tuples later.

Chapter 4

Implementation

4.1 Differences between CPU and GPU hardware

Before detailing the specific algorithms used by the RubiCL project, it is necessary to contrast two of the heterogeneous target architectures.

CPU and GPU architectures have diverged significantly due to differing traditional applications.

CPU devices have had a long history of optimisation for sequential processing. As such, they have high clock-speeds and integrated hardware designed to increase instruction throughput; Modern processors rely heavily on *branch predictors* and identifying opportunities for speed-up via *out-of-order execution*.

Conversely, the graphics pipeline tends to mainly utilise Single Instruction, Multiple Data (SIMD) operations. These consist of periods where the same few calculations are applied to vast quantities of data. With this execution pattern, complicated optimising hardware and higher clock-speeds are less favourable. Instead, hardware designers achieve incredible throughput by placing many massively parallel, yet simple, execution units on a single chipset.

In short, common GPU hardware lacks many optimisations targeting single-threaded performance. More significantly, devices lack the ability to branch by jumping between instructions during execution. Instead, a flat sequence of instructions is processed by the hardware scheduler. Conditional logic is provided by condition-variable flags set on individual instructions. These masking flags state whether execution of each statement within a branch segment should occur.

The inability to jump causes code that branches to become necessarily inefficient. Any branching logic within a kernel will leave some execution units idling until the code path converges again.

Luckily, GPU devices compensate by being exceptional at tasks resembling those that they were designed for: SIMD computation patterns. A high-end GPU, such as the *Radeon R9 290X*, can contain as many as 44 compute-units. Each compute-unit is capable of scheduling 64 concurrent SIMD operations. At full utilisation, this vastly outperforms the raw instruction-rate of any CPU device. The amount of throughput possible in a latest-generation desktop GPU is simply several orders of magnitude higher.

The goal of this project’s implementation phase is to produce an easy-to-use library that presents significant throughput gains to an end-user performing common tasks.

4.2 Parallel primitives

4.2.1 Map

Map is a higher-order function that mutates all elements in a provided input vector, by applying a function parameter. It can be used to concisely describe a uniform alteration. Map is simple to parallelise since no sharing of each individual thread’s state is required.

Algorithm 1 *Map* higher-order function with sequential execution.

```

function SeqMap( $f, A$ )
  for all  $a_i \in A$  do
     $a_i \leftarrow f(a_i)$ 
  end for
end function

```

Algorithm design Upon examining the sequential implementation of the map primitive shown in Algorithm 1, it is clear that iteration i only reads and writes value a_i .

The dependency graph for a map of $\|A\| = 6$ is shown in Figure 4.1.

Figure 4.1: *Map* dependency graph



When analysing data-dependency graphs, such as the one above, any partitioning that doesn’t sever edges denotes a valid parallel strategy. Since Figure 4.1 contains no inter-node dependencies, it is trivial to schedule the task concurrently on many compute-units. The map task is *embarrassingly parallel*.

Algorithm 2 *Map* higher-order function with parallel execution.

```

function ParMap( $f, A$ )
  in parallel, for  $a_i \in A$ 
     $a_i \leftarrow f(a_i)$ 
  end parallel for
end function

```

Equivalent OpenCL kernel design The OpenCL execution model suggests performing tasks over a dataset by scheduling many distinct work-units. As a result, the side-effects of Algorithm 2’s loop body are now provided by the result of many individual kernel-function invocations. Algorithm 3 describes an OpenCL kernel that performs map computation with a size $\|A\|$ work-group.

Algorithm 3 Map higher-order function in OpenCL kernel form.

```

 $f \leftarrow \text{MutationFunction}$ 
function MapKernel( $A$ )
  DeclareVariables( $f$ )
   $i \leftarrow \text{GetGlobalID}$ 
   $a_i \leftarrow f(a_i)$ 
end function

```

Alternative kernel investigation

Motivation After producing a system that performs map parallelisation akin to Algorithm 3, suspicion arose over whether it was excessive to schedule one work-unit per element. With traditional threaded programming, there is a significant performance cost when creating each parallel subroutine. In addition, with many kernel invocations all writing to offsets in the globally-available A , it was theorised that large numbers of competing memory access requests would hamper throughput.

Kernel adaption In order to ensure that any anticipated scaling issues were avoided, a new kernel design was constructed. The alternate design avoids scheduling a number of work-units greater than the number of compute-units present.

Algorithm 4 Map higher-order function in reduced-work-unit OpenCL kernel form.

```

 $f \leftarrow \text{MutationFunction}$ 
 $width \leftarrow \lceil \frac{\|A\|}{\text{compute\_units}} \rceil$ 
function MapKernel( $A, width, \|A\|$ )
  DeclareVariables( $f$ )
   $i \leftarrow \text{GetGlobalID}$ 
   $i_{\text{initial}} \leftarrow i \times width$ 
   $i_{\text{next}} \leftarrow (i + 1) \times width$ 
  for  $i \in ((i_{\text{initial}} \dots (i_{\text{next}} - 1) \cap (i_{\text{initial}} \dots (\|A\| - 1)))$  do
     $a_i \leftarrow f(a_i)$ 
  end for
end function

```

The adapted kernel, now performing map computation using a size $\|CU\|$ work-group, is presented in Algorithm 4.

Results After benchmarking the execution time of the kernels presented in Algorithms 3 and 4, no significant difference in performance was found. This suggests that the overhead for work-unit scheduling within the OpenCL framework is very low. It also suggests that simultaneous access to neighbouring global-buffer elements does not affect latency worse than strided simultaneous access.

Influenced by these findings, the decision was made to use Algorithm 3 for map tasks. This is due to the design being conceptually simpler, and therefore choosing the most basic solution that works well.

4.2.2 Scan

It is easier to explain the operation of the scan primitive after an explanation of Reduce has been given. Reduce is a higher-order function that takes an array and an initial ‘result’ value (usually an identity value) and then repeatedly applies a combining function to produce an output.

The final result is equivalent to repeatedly updating the initial value with the output of itself and the next set member using the combiner. Using this technique, the input array is consumed once while the result is cumulatively generated. Any associative reduction function can be parallelised to increase throughput.

A well-known example of reduction is when the initial value is 0 and the combining function is $+(x, y)$. This results in *summation* of an input dataset.

Scan is similar to Reduce in that it takes an input vector and a combining function.

Instead of returning the final result, Scan returns a vector that is equal to the intermediate values produced, if the combining function was incrementally applied from one end of the dataset to the other. Scan can also exploit a highly-parallel architecture when supplied with suitable operators.

Algorithm 5 *Inclusive Scan* higher-order function with sequential execution.

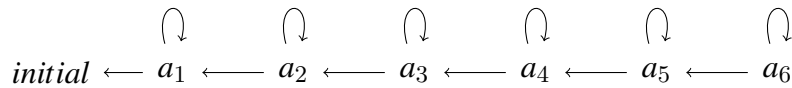
```

function SeqScan( $f, a_{-1}, A$ )
  for all  $a_i \in A$  do
     $a_i \leftarrow f(a_{i-1}, a_i)$ 
  end for
end function

```

Algorithm design Unlike sequential map, iteration i now reads from both a_{i-1} and a_i in addition to writing a_i . This produces a data-dependency graph with greater connectedness, shown in Figure 4.2

Figure 4.2: *Inclusive Scan* dependency graph



It is clear that no partitioning of this graph exists that does not sever edges. Therefore, this task is not embarrassingly parallel.

However, this does not mean that all hope is lost. It is possible to efficiently parallelise a scan task, but it requires performing computation split over multiple *stages*. One method for achieving this is demonstrated in Figure 4.3.

A parallel algorithm’s *cost* is defined as its asymptotic run-time multiplied by the required number of compute-units.

The *odd-even* prefix sum algorithm can process a dataset of size n in $O(\log n) + \frac{O(n)}{\|CU\|}$ stages of execution. This gives a cost of $O(\|CU\| \log n) + O(n)$. Importantly, it is *cost-optimal*, meaning

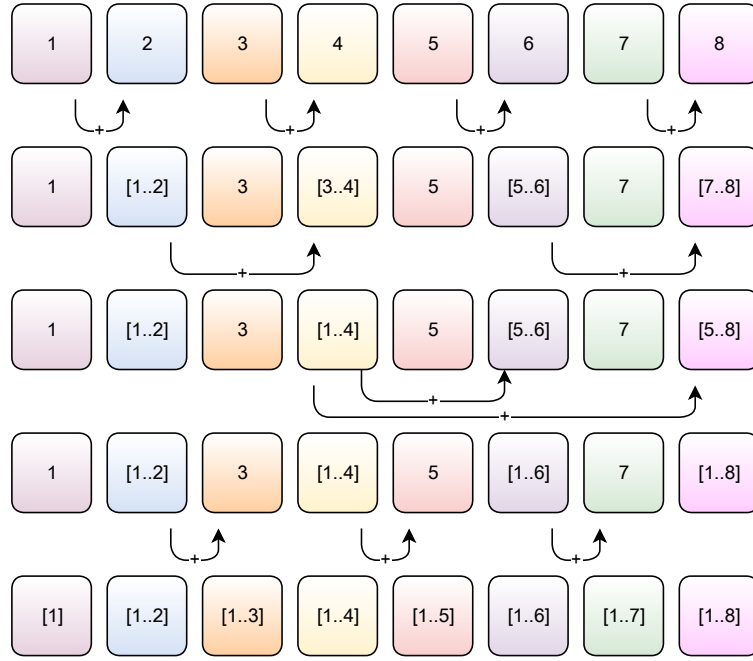


Figure 4.3: An example of parallelised *inclusive scan* using the *odd-even* algorithm, detailed in Algorithm 6

that its cost is equal to that of the best-known sequential algorithm, when $\|CU\| = O(\frac{n}{\log n})$. This is an entirely reasonable assumption given large datasets and the comparatively low number of compute-units (4 – 48) present on commodity OpenCL devices.

This discovery suggests that it is possible to increase the throughput of scan tasks significantly, by scheduling them across massively parallel OpenCL devices.

4.2.3 Scatter

The Scatter primitive receives an input array A , an array of indices I , and an output array B . It updates B such that $B_{I_i} \leftarrow A_i$. Put otherwise, it inserts the value given at offset i of A into B , at the position given by the value at offset i of I .

Scatter is useful for reordering a collection or projecting a subset of an input dataset into an output dataset.

Permutation scatter It is important to draw attention to an important distinction in types of scatter operation. *Permutation Scatter* is defined as a scatter operation where all $i \in I$ are unique. Therefore, there are no two writes to the same destination in B . Other forms of scatter increase complexity, as rules that state how to handle write collisions within the transaction must be introduced.

Luckily, for this project's needs we only need to analyse the simpler *permutation scatter*. We can assume that no two writes to the same destination offset will occur.

A data-dependency graph for a typical scatter operation is shown in Figure 4.4. At first, it may appear complicated. However, when nodes $b_i \in B$ are reordered by their data-source, a valid partitioning becomes clear. The result of this simplification is shown in Figure 4.5.

Algorithm 6 Odd-even style *Scan* higher-order function with parallel execution.

```

function ParScan( $f, A$ )
   $level \leftarrow 2$ 
  while  $level \leq \|A\|$  do
    in parallel, for  $l \in (level \dots 2 \times level \dots \|A\|)$ 
       $A_l \leftarrow f(A_l, A_{l - \frac{level}{2}})$ 
    end parallel for
     $level \leftarrow 2 \times level$ 
  end while
  if  $level = \|A\|$  then
     $level \leftarrow \frac{level}{2}$ 
  end if
  while  $level > 1$  do
    in parallel, for  $l \in (level + \frac{level}{2} \dots 2 \times level + \frac{level}{2} \dots \|A\|)$ 
       $A_l \leftarrow f(A_l, A_{l - \frac{level}{2}})$ 
    end parallel for
     $level \leftarrow \frac{level}{2}$ 
  end while
end function

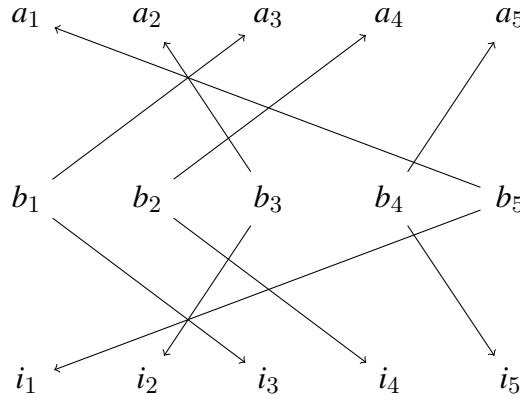
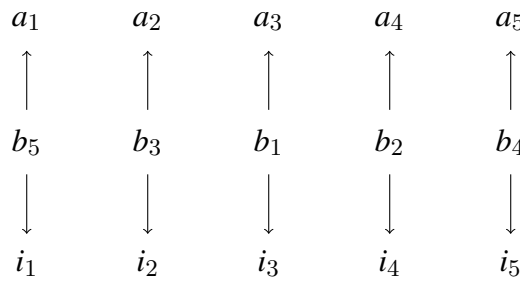
```

Algorithm 7 *Scatter* primitive with sequential execution.

```

function SeqScatter( $A, I, B$ )
  for all  $a_i \in A$  do
     $B_{I_i} \leftarrow a_i$ 
  end for
end function

```

Figure 4.4: *Permutation Scatter* dependency graph**Figure 4.5:** *Permutation Scatter* dependency graph, simplified.

This suggests that scatter, when using unique indices, is *embarrassingly parallel*. Like map, this produces an easy-to-understand parallel conversion, shown in Algorithm 8.

Algorithm 8 *Permutation Scatter* primitive with parallel execution.

```

function ParScatter( $A, I, B$ )
  in parallel, for  $a_i \in A$ 
     $B_{I_i} \leftarrow A_i$ 
  end parallel for
end function

```

Equivalent OpenCL kernel design The kernel design is simpler than that of map, since function side-effects do not need to be included. It is presented in Algorithm 9.

4.2.4 Filter

`filter` is a higher-order function that applies a predicate function on elements of a dataset. It returns the subset of the input vector for which the predicate evaluates true.

A sequential implementation of the primitive is shown in Algorithm 10.

Checking the predicate is simple to do in parallel, since whether to keep each element depends only on the value of that element. However, producing and returning the subset is significantly more

Algorithm 9 *Permutation Scatter* primitive in OpenCL kernel form.

```

function ScatterKernel( $A, I, B$ )
   $i \leftarrow \text{GetGlobalID}$ 
   $B_{I_i} \leftarrow A_i$ 
end function
  
```

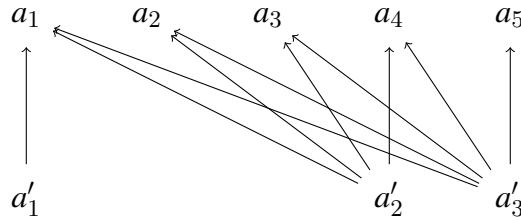
Algorithm 10 *Filter* higher-order function with sequential execution.

```

function SeqFilter( $A, predicate$ )
   $Result \leftarrow [ ]$ 
  for all  $a_i \in A$  do
    if  $predicate(a_i)$  then
       $\text{Push}(Result, a_i)$ 
    end if
  end for
   $A \leftarrow Result$ 
end function
  
```

involved. Complication stems from the position of each kept item in the output array depending on the state of previous elements in the input vector.

Figure 4.6: *Filter* dependency graph.



The filter operation is clearly not *embarrassingly parallel*. However, there is no need to search for an involved parallel algorithm. We can construct an efficient filter operation by reusing the previously defined parallel primitives, map, scan, and scatter. This insight transforms a hard problem into one that is much easier to solve.

Composing a parallel solution The first stage of producing a parallel filter primitive is recognising the distinct data dependencies:

1. Whether an element is kept.
2. Where any kept element appears in the result.
3. The total number of elements kept, since we cannot dynamically allocate memory.

Identifying kept elements The information required by dependency 1 can be obtained by performing a map task on the dataset using the predicate function. The sole difference is that the result should be stored in a new buffer instead of overwriting the previous value.

Assuming we have an input vector A and a newly created predicate buffer P , we now know that any A_i should be kept if, and only if, P_i .

Knowing where to place kept elements Once we have produced a predicate buffer, via 1, we can easily derive the destination of kept elements (2). If the predicate buffer is stored as a vector of bit-flags, the number of kept elements at point P_i is equal to element i of the prefix-summation of P . This connection is illustrated in Figure 4.7

Figure 4.7: Using prefix-sum to determine insertion points.

$$predicate = \text{keep_if_even}$$

Input dataset	0	1	2	3	4
Presence buffer	1	0	1	0	1
Prefix sum	1	1	2	2	3
Insertion point	0	-	1	-	2

The translation from prefix-summed buffer element to insertion point is just an off-by-one adjustment. Furthermore, since map followed by scan is cost $O(n) + O(n) = O(n)$, we can obtain these insertion points *cost-optimally*.

Counting the number of kept elements Following the calculation of dependencies 1 and 2, obtaining 3 is trivial. It is simply the final element of the prefix-sum buffer. This can be retrieved by a single lookup after the other sub-problems have been solved.

Complete solution By utilising map, scan, and a conditional-modified scatter, filter can be performed with cost $O(n) + O(n) + O(1) + O(n) = O(n)$. This is identical to the sequential algorithm presented earlier and is therefore *cost-optimal*. Again, this suggests that filter tasks can benefit from increased throughput when scheduled across multiple compute-units.

The combined process is demonstrated in Algorithm 11.

Algorithm 11 Filter higher-order function with parallel execution, composed from other primitives.

```

function ParFilter( $A, p$ )
   $P \leftarrow \text{ParMap}(A, p)$ 
   $I \leftarrow \text{ParScan}(P, +)$ 
   $B \leftarrow \text{Zeros}(I_{||I||})$ 
  in parallel, for  $a_i \in A$ 
    if  $P_i$  then
       $B_{I_i-1} \leftarrow A_i$ 
    end if
  end parallel for
   $A \leftarrow B$ 
end function

```

The parallel loop body is a modified version of the scatter task. The divergence is that it only performs scattering if the predicate element is set.

4.2.5 Count

The count function is very similar to the aforementioned `filter` primitive. Instead of returning the subset of a dataset that passes a predicate, it returns how many times the predicate was passed.

To avoid writing extra code providing counting functionality, we can re-use many components of the `filter` implementation. Namely, the `map` task that sets predicate bits for each element, followed by the `scan` task to yield the number of kept elements. Reduction can be performed in less work than a `scan` primitive, as the intermediate values are not required. However it is asymptotically identical, therefore the `scan` primitive can be reused to reduce developer workload. Further work can include replacing this suboptimal lack of specialisation with a faster reduction task.

4.2.6 Sort

The project's sorting capability is provided by parallel *bitonic mergesort*. Bitonic sorting utilises a sorting network of comparators to gradually produce a monotonically sorted result, from stages of increasing length bitonic sequences.

A simple implementation of bitonic mergesort, whereby single elements are compared and possibly swapped at each gate, can sort an input sequence of length n with $O(n \log^2 n)$ cost. This is not cost-optimal as sequential sorting algorithms can perform the task in $O(n \log n)$ comparisons. However, sorting network based algorithms are suitable for SIMD execution as the same sequence of comparisons will always occur, independent of the input elements' values.

The bitonic mergesort kernel, generated and dispatched for all RubiCL's sort tasks, was adapted from sample code for sorting provided within the AMD APP SDK.

4.3 Management System

4.3.1 Converting between Ruby and C objects

One important issue to overcome, when designing an library to accelerate Ruby processing, is the fact that the RubyVM stores all raw values within *objects*, in a manner that is very different from C.

Internally, the RubyVM's C implementation references all objects as of type `VALUE`. This value-type is a slight misnomer as it (usually) contains a pointer to an object structure.

There are several object structures used to represent raw data within the RubyVM. However they all fall into one of two categories:

- `RObject` for storing the state of any bespoke object. This includes storage of instance variables and a pointer to the corresponding class hierarchy for lookup of all methods defined.
- A specialised object representation, used to increase performance of heavily utilised object types. Examples include `RString`, `RFloat`, and `RArray`.

The first member of both aforementioned structures is another structure called `RBasic`. This contains meta-data about the object, such as what type it is. Therefore, it is possible to obtain the

typing information of any object designated by a VALUE, by examining the meta-data present in its first structure member.

Since integers are often heavily utilised within computer programs, and often short-lived, the standard RubyVM implementation avoids the creation of integer objects in order to improve performance. Instead, it encodes the value of the first 2^{64-2} integers directly into the VALUE 'pointer', setting the final 2 bits as the flag 0x01. It can be deduced that a pointer with an odd value is not pointing to a valid memory location, as is true for any pointer that does not align to the machine's word-length boundaries. In this case, a flag lookup table can be used in order to determine the correct typing information.

When dealing with tagged-pointers, the corresponding value of pointer p can be retrieved with $p \gg 1$. To create a tagged-pointer, the value x can be encoded with $(x \ll 1) | 0x01$. The RubiCL project exploits this fact by transferring an array of VALUE pointers directly to the compute-device, whenever annotation has suggested that all contained elements are of Fixnum type. There, the bit-shifting conversions, present at either end of the computation pipeline, can be performed in parallel in order to increase throughput.

4.3.2 Transferring data to and from the compute-device

As OpenCL is designed to provide an abstraction over specific hardware details, the memory management functionality it provides reflects this agnosticism. A common method for providing input data to a compute-device is to explicitly create a buffer of the required size, within the device's *context*, and then enqueue a WriteBuffer task to fill it with any elements to process. This buffer object is then provided as a kernel parameter, prior to kernel invocation. To retrieve the processed elements, a ReadBuffer task is enqueued.

This workflow causes several issues. Firstly, when the compute-device selected is the system CPU, unnecessary data copying occurs. The original location of the dataset is already addressable by the CPU device so there is no need to move elements into a new buffer, this just causes unnecessary delay. The same is true when retrieving processed elements, there is no reason that the host program cannot access the element buffer directly. Secondly, when writing data into the device buffer, data-flow occurs through the host device. This is inefficient on many systems when interfacing with a GPU device, since *kernel-mode* execution is required to transfer data over the Peripheral Component Interconnect (PCI) bus and Operating System (OS)-enforced context switching increases latency.

Luckily, the OpenCL API provides a solution that is better-suited to the project's data transfer needs. *Pinned* buffers can be created by specifying the USE_HOST_PTR flag and providing a pointer to the dataset residing within host memory. When a dataset is pinned, the returned buffer object now merely references the original data location, yet can still be provided as a kernel parameter. Upon providing a pinned buffer parameter, behaviour of the OpenCL execution environment is dependent on the target device. When the kernel is scheduled for execution on the CPU, no memory transfer occurs and the original data can be accessed through the reference provided within a pinned buffer. When the kernel is scheduled for execution on an external device, such as a GPU, Direct Memory Access (DMA) transfer of the dataset occurs and the elements are placed in device-local memory. Before the host program can access the results of kernel execution, the pinned buffer must be

unmapped. At this point it is now guaranteed that the host memory state will reflect the finishing state of compute-device computation.

By utilising pinned memory, the RubiCL library avoids any unnecessary copying of data when executing on CPU compute-devices. In addition, GPU latency is reduced as DMA transfer of the required dataset does not cause the OS to invoke costly context-switching.

4.3.3 Function parser

The system's function parser is responsible for converting a supplied anonymous function into C syntax. The functionality of the parser is demonstrated in Listing 4.1

Listing 4.1: The *LambdaBytecodeParser* converts an anonymous function Ruby object into an array of C expressions.

```
foo = 3
a_function = ->(x){ foo * (2 + x) }
3 #=> #<Proc:0x007f976207ff48@(pry):12 (lambda)>

parser = RubiCL::LambdaBytecodeParser.new(a_function)
#=> #<struct RubiCL::LambdaBytecodeParser
7 #   function=#<Proc:0x007f9761c362c0@(pry):15 (lambda)>>

parser.bytecode
#=> " == disasm: <RubyVM::InstructionSequence:block in __pry__
11 # == catch table
# | catch type: redo    st: 0000 ed: 0016 sp: 0000 cont: 0000
# | catch type: next    st: 0000 ed: 0016 sp: 0000 cont: 0016
# |-----
15 # local table (size: 2, argc: 1 [opts: 0, rest: -1, post: 0,
#                               block: -1, keyword: 0@3] s3)
#   [ 2] x<Arg>
#   0000 trace                256                ( 22)
19 #   0002 trace                1
#   0004 getlocal            foo, 2
#   0007 trace                1
#   0009 putobject           2
23 #   0011 getlocal_OP__wC__0 2
#   0013 opt_plus             <callinfo!mid:+, argc:1, ARGS_SKIP>
#   0015 opt_mult             <callinfo!mid:*, argc:1, ARGS_SKIP>
#   0017 trace                512
27 #   0019 leave"

parser.parsed_operations
#=> [3, 2, "x", "+", "*"]

31 parser.to_infix
#=> ["3 * (2 + x)"]
```

The conversion process occurs over three stages: dumping bytecode, lexing, and reconstruction.

Obtaining function bytecode The bytecode instructions, produced by a compiled anonymous function object, are provided by the `RubyVM::InstructionSequence` module's `disassemble` method. It returns a human readable string that includes all stack-machine instructions.

Lexing bytecode string Instructions of interest are extracted from the human-readable string. This is achieved via a regular expression containing a whitelist of keywords:

```
/(?:\d*\s*(?: (getlocal.*|putobject.*|opt_.*|branch.*).?))/
```

The instructions are then tokenised, by the process detailed in Listing 4.2. The end result is a list of tokens representing stack-machine instructions, in Reverse Polish Notation (RPN).

The heavy reliance on regular expressions to parse bytecode is inelegant and fragile. However, with access only to a human-readable string, and a lack of any formal grammar, it was the best tool at hand to get the job done.

Listing 4.2: Tokenisation rules for lexing human-readable bytecode.

```
def translate(operation)
  case operation
  # First function argument
4  when /getlocal_OP__WC__0 #{function.arity + 1}/
    'x'
  # Second function argument
  when /getlocal_OP__WC__0 #{function.arity}/
8    'y'
  # Indexed bound variable
  when /getlocal_OP__WC__1 \d+/
    id = /WC__1 (?<i>\d+)/.match(operation)[:i].to_i
12    index = locals_table.length - (id - 1)
    beta_reduction locals_table[index]
  # Named bound variable
  when /getlocal\s+\w+,\s\d+/
16    name = /getlocal\s+(?<name>\w+)/.match(operation)[:name].to_sym
    beta_reduction name
  # Literal Zero
  when /putobject_OP_INT2FIX_0_0_C_/
20    0
  # Literal One
  when /putobject_OP_INT2FIX_0_1_C_/
    1
24  # Floating-Point Literal
  when /putobject\s+--?\d+\.\d+/
    operation.split(' ').last.to_f
  # Integer Literal
28  when /putobject\s+--?\d+/
    operation.split(' ').last.to_i
  # Method Sending
  when /opt_send_simple/
32    /mid:(?<method>.*?)/.match(operation)[:method].to_sym
  # Conditionals
  when /branch/
    LOOKUP_TABLE.fetch operation[/branch\w+/.to_sym
36  # Built-in Operator
  when /opt_/
    LOOKUP_TABLE.fetch operation[/opt_\w+/.to_sym
  else
40    raise "Could not parse: #{operation} in #{bytecode}"
  end
end
```

```

44 def beta_reduction variable_name
    function.binding.local_variable_get variable_name
end

```

Algorithm 12 RPN to infix expression conversion.

```

function RpnToInfix(tokens)
    Stack  $\leftarrow$  [ ]
    while length(tokens) > 0 do
        token  $\leftarrow$  shift(tokens)
        if isLiteral(token) then
            push(Stack, token)
        else
            right  $\leftarrow$  pop(Stack)
            left  $\leftarrow$  pop(Stack)
            combined  $\leftarrow$  combine(token, left, right)
            push(Stack, combined)
        end if
    end while
end function

```

Expression reconstruction The final stage of the translation process. It requires converting RPN to infix form. There is a well-defined algorithm for doing so, provided in Algorithm 12.

The conversion algorithm makes the assumption that all non-literals are functions with arity 2. This is justified since it covers all mathematical operators required by the library. Outliers include unary negation and method sending operations. These are detected and handled by an additional level of logic, omitted from the basic algorithm for brevity.

Handling conditionals Conditional operators, such as `&&`, complicate the reconstruction process. Instead of modifying the value of a stack-machine, they may perform a branch. Whether or not this occurs depends on the *truthiness* of the current value. This is caused by the optimisation of short-circuiting boolean calculations.

Luckily, at the point that the branch is possibly triggered, no further operators can mutate the previous value directly. This means that the difficulty of handling branching can be sidestepped by simply abandoning the current expression ending in a conditional, and starting a new stack. All expressions produced are then just combined in order after the token stream has been exhausted.

4.3.4 Task queue

The TaskQueue management system buffers all deferred tasks, scheduled during the computation pipeline. It is responsible for detecting potential optimisations and applying them prior to dispatch. By fusing compatible tasks, the number of passes over the data required can be reduced. The rules utilised to select and process tasks eligible for fusion are detailed in Listing 4.3.

In the order presented, the types of fusion supported are as follows:

Map-map fusion Adjacent map tasks can be replaced by a single task that performs the side-effects of both tasks combined.

Filter-filter fusion Adjacent filter tasks can be replaced by a single task that only retains elements passing both predicates.

Map-filter fusion A filter task following a map task can replace it, performing its mutation before generating presence flags. Filter tasks that have gained the additional responsibility to mutate are hereafter referred to as `mapfilter` tasks.

Filter-map fusion Similarly, a map task following a filter task should not necessarily be scheduled. The side-effects of the map can be performed after filtering by a fused `mapfilter` kernel. This has the disadvantage that branching in the following map task, to avoid unnecessary calculation on items that won't be kept, will cause inefficient stalling in execution. However, if enough work-units are scheduled, the OpenCL run-time can identify non-stalled units to swap-in. Nonetheless, time wasted by stalls in a fused kernel is insignificant compared to the time to schedule a new kernel and pass over the data again in a separate map task.

Map-mapfilter fusion No different to map-filter fusion. The side-effects of the replaced map task are prepended to the `mapfilter`'s preprocessing actions.

Mapfilter-map fusion Again, advantageous as it avoids scheduling another pass over the data. The side-effects of the unnecessary map are appended to the `mapfilter`'s post-processing actions.

Mapfilter-filter fusion In `mapfilter` tasks that have no post-processing actions, the filter segment can be updated in the same manner as when undergoing filter-filter fusion.

Listing 4.3: Fusion rules for combining tasks within the *TaskQueue*.

```
@tasks = @tasks.reduce [] do |queue, task|
2  if (*fixed_queue, previous = queue).empty? then [task]
    else
      case [previous.class, task.class]
      when ([RubiCL::Map] * 2), ([RubiCL::Filter] * 2)
6        fixed_queue << previous.fuse!(task)

      when [RubiCL::Map, RubiCL::Filter]
        fixed_queue << RubiCL::MappingFilter.new(
10          pre_map: previous, filter: task)

      when [RubiCL::Filter, RubiCL::Map]
        fixed_queue << RubiCL::MappingFilter.new(
14          filter: previous, post_map: task)

      when [RubiCL::Map, RubiCL::MappingFilter]
        fixed_queue << task.pre_fuse!(previous)
18

      when [RubiCL::MappingFilter, RubiCL::Map]
        fixed_queue << previous.post_fuse!(task)

22  when [RubiCL::MappingFilter, RubiCL::Filter]
    if previous.has_post_map?
      fixed_queue << previous << task
    else
```

```
26     fixed_queue << previous.filter_fuse!(task)
      end
    else
      fixed_queue << previous << task
30    end
  end
end
```

Options to turn-off TaskQueue optimisation were introduced so that the magnitude of benefits can be studied.

4.4 Functionality Testing

A performant system for calculation parallelisation isn't much use if its behaviour is incorrect. In order to increase confidence that the system performs as expected, the library was developed alongside a comprehensive test suite.

Having significant tests around behaviour enables more intrusive alterations to occur smoothly. This allowed the pace of experimentation to increase. New ideas can be verified as resultant in enhanced performance, without introducing behaviour regressions.

The RSpec[21] testing library was used to produce test-cases. It presents a DSL for defining the intended behaviour of objects.

By describing a context corresponding to each feature that an subcomponent is designed to present, and testing boundary cases within that context, a rigid specification of correct behaviour was defined.

The advantages of testing were significant in terms of effort-economy. With a full test-suite execution taking less than 100ms on the development laptop, it was responsive enough to be triggered by each updated file within the development directory. This immediately highlighted interface clashes and regressions introduced during development. In addition, it reduced the amount of time wasted, manually checking that the system performed as advertised.

Compared to the stressful development practices of other projects witnessed, this development style is subjectively judged to be a significant success of the project.

4.5 Performance testing

A stated goal of the project refers to "improving dynamic language performance". Therefore, it is important that the project provides a method for producing meaningful metrics. In order to facilitate measurement, a benchmarking suite for easy graph creation was developed. In addition, an execution mode that displays timing information alongside results was added to the Logger.

4.5.1 Custom benchmarking environment

During the lifetime of the project, a benchmarking library was created. It was originally designed as personal project, but was utilised heavily during development of the library. The *Asymptotic* library eases the production of graphs that plot function run-time over a range of input sizes.

A user provides several parameters to the library:

- A name for the graph.
- The number of iterations to average benchmark results over.
- Several function descriptions to test.

Each function description also contains parameters:

- A description of what is being benchmarked.
- An `Enumerable` providing seeds to the benchmark environment.
- A function that turns each seed into an *input*. This could be any value, given to the benchmarked function, that responds to `size`.
- The function to benchmark.

The benchmarking environment was used to produce Figure 2.1, shown earlier in the *Overview* chapter. The code used to generate the graph is shown in Listing 4.4.

Listing 4.4: The *asymptotic* library used to generate quick benchmark graphs.

```
require 'asymptotic'
require 'ostruct'

4 seeds = (20..25)

ruby_input = {
  input_seeds: seeds,
8  input_function: ->(seed){ (1..2**seed).to_a }
}

command_line_input = {
12  input_seeds: seeds,
  input_function: ->(seed){
    OpenStruct.new.tap { |s| s.size = 2**seed }
  }
16 }

Asymptotic::Graph.plot(5, "squaring integers and filtering evens",
  "Ruby: Enumerable#map and Enumerable#filter" => {
20  function: ->(array){
    array.map { |x| x * x }.select { |x| x % 2 == 0 }
  },
  }.merge(ruby_input),

24  "C: loop for mapping followed by loop for filtering" => {
    function: ->(struct){ `./just_c.o #{struct.size}` },
  }.merge(command_line_input),
```


28)

The library handles generating an average run-time, using the specified number of test iterations, for each $(function, ||input||)$ pair. The garbage collector is turned off for the duration of each test and manual sweeping is triggered after each measurement is taken. A graph is then produced, using the `gnuplot` library, that compares the performance of all provided functions.

The ability to effortlessly create run-time graphs, for arbitrary given functions, proved useful during experimental development. When changes were introduced into the codebase, corresponding feature flags were added to the configuration module. Then, the benchmark environment was used to plot the performance of the feature turned off against the performance with the feature enabled. This made it easy to highlight changes in design that altered performance for a given task over a variety of input sizes.

4.5.2 Segmented timing information from execution environment

Overall execution time is an important metric. However, it is helpful to be able to tell what proportion of time is spent doing various tasks during run-time.

In order to achieve this, code that gathers timing information was introduced to the library's native extensions that interact with hardware devices.

With each action triggered by the system, the resultant transaction time was measured. The low-level code, handling device management, obtains measurements via observing the start and stop time of OpenCL library functions. This data could then be retrieved by the library and inspected to determine the duration of subtasks, transferring or processing data.

Execution duration measurements are taken by native interaction modules, and presented to the management system. To make these readings available, configuration flags were added to the `Logger` stating that this data should be displayed during run-time.

An example of the finer granularity of timing information presented is given in Listing 4.5.

Listing 4.5: Segment times presented during command execution.

```
RubiCL::Logger.show_timing_info = true
#=> true

4 (1..10)[Int].map { |x| x + 100 }.filter { |y| y.even? }[Fixnum]
#> Pipeline Started
#> Pinned Integer Range in 0.039 ms
#> Enqueued
8 #> (rubiclmappingfilter5 =>
#> [
#>   "x = x >> 1", "x = x + 100",
#>   "?{(x % 2 == 0)}?", "x = (x << 1) | 0x01"
12 #> ]
#> )
#> in 3.175 ms
#> Waiting for in-progress tasks took 0.004 ms
16 #> Retrieved 5 Integers in 0.017 ms
#> Pipeline Complete in 5.109 ms
```

```
#=> [102, 104, 106, 108, 110]
```


Chapter 5

Evaluation

This chapter describes the means by which the project's success will be evaluated. Since both subjective and objective goals are stated in the *Overview* chapter, this will be taken into account when constructing evaluation criteria.

The results of individual evaluation procedures will be presented in the *Results* chapter, and interpreted in the corresponding *Analysis* section.

5.1 Recap of project aims

5.1.1 Objective goals

Improving Ruby language performance when executing tasks on datasets In order to investigate whether exploitable performance improvements are given by the completed project, a series of scenario-driven benchmarks were constructed. The library was then utilised to perform these scenarios and execution duration was compared to competing solutions: standard Ruby code, and bespoke native extensions developed solely to achieve the evaluated task. Further discussion of all benchmarking will be presented in the *Benchmarking* subsection.

Increasing the scale of REPL experimentation possible This goal depends on favourable results in the previous evaluation criteria, as improved performance should lead to better REPL response time. However, unlike the previous benchmark's contenders, there is no longer a need to consider bespoke low-level solutions. This is due to the assumption that not all code is written upfront when investigating data using a REPL. As such, someone employed to analyse and draw conclusions from a dataset may not have the skill-set required to produce low-level code on demand.

5.1.2 Subjective goals

Gracefully extending the Ruby language run-time In order to judge how well the library is designed from a usability perspective, a series of user trials were conducted. Each trial presented a participant with a task description to solve, with the use of the RubiCL library. Notes were taken on applicant performance, specifically whether they had difficulties using the project's deliverable. Experimental design will be discussed in further detail in the *User Evaluation* section.

Effective reuse of OpenCL code Progress towards this goal will be summarised later by a discussion on code reuse within the project, highlighting any successes.

Suitability for deployment on unseen systems Portability is hard to measure. There is a near-infinite number of system configurations that could benefit from parallelism libraries. Instead of focusing on trying to install the library on as many systems as possible, installation from scratch was attempted on a typical desktop system. The results of this installation will be presented, and compared to the library's performance on the development system.

5.2 Benchmarking

5.2.1 Range of tests

The benchmarking procedure is responsible for investigating how successful the project was with regards to its performance-oriented goals. As such, it must be designed in a way that demonstrates the potential performance of the system, as well as being representative of realistic usage.

The decision was made to test the variety of system primitives in isolation, in addition to a combined task that produces a fused kernel. The range of primitives shortlisted for investigation were as follows:

- A basic map task, incrementing the dataset.
- A 'dense' filter task returning 50% of the input data.
- A 'sparse' filter task returning 5% of the input data.
- A fused mapfilter task, consisting of the previous map task followed by the dense filter task.
- A sort task.

5.2.2 Test systems

5.2.2.1 Hardware

Two systems were used for running tests, the *MacBook* laptop used primarily for development and the ordered AMD desktop system. With library development and regular testing occurring primarily

on the laptop, the benchmarking procedure provided an opportunity to evaluate how portable the performance characteristics of the OpenCL framework are.

The specification of the development laptop was as follows:

APU 1.7 GHz Intel *Core i7 Haswell* with Intel HD5000 Graphics

RAM 8GB 1600Mhz DDR3

The specification of the desktop system, used for performance testing, was as follows:

CPU AMD *FX-4120*

GPU AMD *R7 260X*

RAM 16GB 1600Mhz DDR3

5.2.2.2 Software

For both hardware systems, several methods of performing each specified task were measured:

- The standard implementation provided by unmodified Ruby 2.2.
- A handwritten native extension that performs the task using the optimal sequential method. (Listing 5.1)
- The RubiCL library performing the task, executing on the system CPU.
- The RubiCL library performing the task, executing on the system GPU.

The standard implementation was included as it is important that a comparison between any new solutions and existing functionality is made.

The reason to additionally measure the performance of a bespoke native extension performing the task is as follows:

By investigating sequential, best-case performance, we can deduce whether performance gains stem purely from parallelism or instead more-optimal execution. If the library exceeds performance of the best possible sequential implementation, throughput of the compute-device has been harnessed effectively. Otherwise, assuming that the standard implementation performance is exceeded, one of two things is true: Either the library provides throughput gains but the overhead of scheduling parallel tasks through OpenCL mitigates any potential improvements. Or, the throughput provided by the increased number of execution units is not enough to compensate for the extra work encountered by the parallel algorithms employed.

The project's performance on both hardware devices present in the test system was measured, again by recording task execution duration, so that the relationship between the type of task and the optimal device architecture can be investigated.

Listing 5.1: Custom native extension performing benchmarked tasks in the optimal sequential manner.

```
1 #include "ruby.h"

VALUE mMapAddOne(VALUE self, VALUE input) {
    int elements = RARRAY_LEN(input);
```

```

5  VALUE output = rb_ary_new2(elements);

    for (int i = 0; i < elements; ++i) {
        VALUE transformed = INT2FIX(FIX2INT(rb_ary_entry(input, i)) + 1);
9      rb_ary_store(output, i, transformed);
    }

    return output;
13 }

VALUE mFilterEven(VALUE self, VALUE input) {
    int elements = RARRAY_LEN(input);

17     int kept = 0;
    int size = 2;
    VALUE* out = malloc(size * sizeof(VALUE));

21     for (int i = 0; i < elements; ++i) {
        VALUE entry = rb_ary_entry(input, i);
        if (FIX2INT(entry) % 2 == 0) {
25             if (++kept > size) {
                out = realloc(out, (size *= 2) * sizeof(VALUE));
            }
            out[kept - 1] = entry;
29         }
    }

    VALUE output = rb_ary_new2(kept);
33     for (int i = 0; i < kept; ++i) rb_ary_store(output, i, out[i]);
    free(out);

    return output;
37 }

VALUE mFilterModTwen(VALUE self, VALUE input) {
    int elements = RARRAY_LEN(input);

41     int kept = 0;
    int size = 2;
    VALUE* out = malloc(size * sizeof(VALUE));

45     for (int i = 0; i < elements; ++i) {
        VALUE entry = rb_ary_entry(input, i);
        if (FIX2INT(entry) % 20 == 0) {
49             if (++kept > size) {
                out = realloc(out, (size *= 2) * sizeof(VALUE));
            }
            out[kept - 1] = entry;
53         }
    }

    VALUE output = rb_ary_new2(kept);
57     for (int i = 0; i < kept; ++i) rb_ary_store(output, i, out[i]);
    free(out);

    return output;

```

```

61 }

VALUE mMapAddHalfFilterEven(VALUE self, VALUE input) {
    int elements = RARRAY_LEN(input);

65     int kept = 0;
    int size = 2;
    int* out = malloc(size * sizeof(int));

69     for (int i = 0; i < elements; ++i) {
        int entry = FIX2INT(rb_ary_entry(input, i));
        entry += entry / 2;
73         if (entry % 2 == 0) {
            if (++kept > size) {
                out = realloc(out, (size *= 2) * sizeof(int));
            }
77             out[kept - 1] = entry;
        }
    }

81     VALUE output = rb_ary_new2(kept);
    for (int i = 0; i < kept; ++i) rb_ary_store(output, i, INT2FIX(out[i]));
    free(out);

85     return output;
}

void Init_bespoke_backend() {
    VALUE BespokeBackend = rb_define_module("BespokeBackend");
89     rb_define_singleton_method(BespokeBackend, "map_add_one",
        mMapAddOne, 1);
    rb_define_singleton_method(BespokeBackend, "filter_even",
        mFilterEven, 1);
93     rb_define_singleton_method(BespokeBackend, "filter_modtwen",
        mFilterModTwen, 1);
    rb_define_singleton_method(BespokeBackend, "map_add_half_filter_even",
        mMapAddHalfFilterEven, 1);
97 }

```

5.2.3 Variety of data-types

The RubiCL library supports accelerating computation on homogeneous collections of both `Fixnum` and `Float` objects. However, presenting benchmarks of the full range of parallel primitives on both types and both systems, then commenting in depth on both graphs, would provide a lot of redundant data.

Instead, the performance of the library on integer datasets, across both hardware systems, will be explored in depth. This will be followed by a brief analysis of how performance differs when presented with floating-point datasets.

The major difference when operating on `Float` objects, is that they lack tagged-pointers. Therefore, the value of each object present must be determined by dereferencing the object pointer and examining the resultant `RFloat` struct. This is impossible to achieve in parallel on an external hardware

device, unlike when bit-shifting the tagged-pointers of `Fixnum` objects. In addition, new `RFloat` objects must be created to wrap the computed results. These two stages of extra computation must also be performed by the RubyVM implementation, therefore the RubiCL library should not be significantly disadvantaged.

It is also worth mentioning the difference in hardware performance concerning integer and floating-point operations. While tasks scheduled on the CPU should utilise the same execution units as the RubyVM, tasks scheduled on the GPU may be affected by how well the hardware is suited to floating-point calculations.

The two factors mentioned result in a linear increase in pre-processing and post-processing time, and a possible rate-of-computation shift. Therefore, they can be summarised by merely presenting the lower-bound at which computation becomes worth outsourcing for both data-types, alongside measurement of the total speed-up rate achievable.

Lack of ‘double’ support on Intel HD5000 Unfortunately, the GPU present on the testing laptop does not support calculation on double-precision floating-point numbers. As a result, the floating-point benchmarks presented only document CPU performance. This means that merely the linear processing addition, and not the rate-of-computation change, can be commented on.

5.2.4 Method

5.2.4.1 Gathering results

In order to speed up the process of gathering many benchmark results, a simple utility was produced. Listing 5.2 shows the internals of the *benchmark helper* utility.

Since Ruby is a language that provides automatic memory management and garbage collection of objects, these features must be disabled when benchmarking. Otherwise, the large number of repeated tests may trigger a sudden stop-the-world sweep during the latter timing rounds and skew the results.

To ensure that the results gathered represented average use effectively, each benchmark, at a particular dataset size, was run 20 times. Task execution duration was recorded over all repetitions, the mean of which was then returned. This lessens the weighting of anomalous readings, when the system’s external utilisation may have reduced performance slightly.

Listing 5.2: Helper function defined for benchmarking a block of code.

```
require 'benchmark'

3 def benchmark(times: 1, input:[], &block)
  GC.start
  (1..times).map do
    GC.disable
7    time_taken = Benchmark.realtime { block.call(input) }
    GC.enable
    GC.start
11    time_taken
  end
end
```

```

    end.inject(&:+).to_f / times
  end
end

```

Gathering readings using the helper function involved substituting the block argument with the implementation to test, and calling the utility over a range of sizes. Once obtained, the readings for each set of competing software elements were written to disk, available for the graph generation process to consume. Listing 5.3 shows a typical method of gathering the set of results for a standard Ruby *MapFilter* task.

Listing 5.3: Using the benchmark helper to gather readings over a range of input datasets.

```

require './bench_helper'

3 results = (1..19).step(2).map do |millions|
  dataset = Array(1..millions * 1_000_000)
  benchmark(times: 20, input: dataset) do |d|
    d.map { |x| x + 1 }.select { |x| x.even? }
7   end
end

```

5.2.5 Issues

One issue experienced whilst collecting results was the fluctuation in APU performance on the test laptop.

Likely due to system heat management protocols, if too many benchmarks were run in quick succession, the performance of the on-board GPU would decrease.

This was unrealised for a significant portion of the project's implementation phase. Initial benchmarking methods, relied on throughout library construction, ran all tests at once, with the CPU sub-system and then the GPU sub-system being tested. As a result, laptop GPU performance was consistently under-estimated. Luckily, this outside factor was realised as final benchmarks were being designed. As a result, care was taken to reduce the length of benchmark runs and instead schedule more subsets of the desired test range, allowing device temperature to stabilise between measurements.

5.3 User Evaluation

5.3.1 Subjects

The user evaluation procedure was designed to both showcase the potential of the project, when applied to a realistic scenario, and highlight any usability issues of the library. 7 applicants were recruited for a 5 question challenge, using RubiCL to answer questions about a dataset.

The fictitious scenario presented was that of an online banking service with two separately stored datasets, corresponding to the triggering `user_id` and transfer amount of the past 10 million transactions. Subjects had to utilise higher-order primitives to summarise activity presented in the data, under the guise of investigating a suspicious user.

When searching for potential test-subjects, care was taken to explore a variety of backgrounds and programming proficiencies. As such, the range of applicable skills present in users evaluated ranged from high levels of parallel programming experience to barely any programming experience whatsoever.

5.3.2 Method

Before testing began, each test-subject was shown a quick demonstration of the project's capabilities, alongside a discussion about the research goal. The aim of this quick demonstration was to hint at how the library may be applied to the later provided problems, in addition to an introduction or refresher to Ruby's syntax for higher-order functions. After the demonstration concluded, a link[22] containing brief API documentation was provided. The majority of documentation was lifted directly from the Ruby documentation source, as the library mirrors the `Enumerable` API closely. The few additional methods documented were RubiCL specific functionality such as the bifurcation of tuple buffers. The hint document was provided so that stuck or novice users could remind themselves of basic language functionality. Care was taken as to not reveal how to solve problems directly.

Users were provided with a skeleton file, containing a DSL for answering several given questions. Each question accepted an anonymous function response, with bound variables signifying the resources that could be used to answer the query. To respond, each applicant would replace the body of the function, originally a placeholder method, with the required query pipeline.

Subjects were unaware that the provided dataset variables were actually file handles, pointing to large collections of integer data on disk. In addition, the test system GPU was assigned as the default RubiCL compute-device.

Users were encouraged to save the test file each time a function body had been specified. An analysis program, listening on file-system events in the working directory, would then call the provided functions, providing test data, and report whether answers given were correct. This gave immediate feedback to subjects as to when they should move on as particular question was solved. In addition to verifying calculated answers, reports of the time taken for each task were collated.

Notes were taken during the study, followed by brief discussion with each finished applicant. Further discussion of user evaluation results and analysis will occur in the *Results* chapter.

5.3.2.1 Issues

User evaluation took place late in the project's life-cycle. As a result, many potential candidates were reluctant to participate as they were busy working on their own projects. Scheduling this session earlier would have helped avoid this.

Another reason to schedule the session earlier is the benefit of using feedback to guide design. Luckily, most constructive criticism resultant from the user evaluation trials was simple enough to fix quickly. However, any significant issues would be realised too late before the project's deadline to justify an intrusive overhaul.

Listing 5.4: The test file full of questions given to each subject.

```

require_relative './evaluation/user_test.rb'

# Imagine that you run a hugely successful bitcoin exchange that hasn't gone bust yet.
4 #
# You have access to logged details of the last 10 million transactions, semi-structured form.
# The following variables represent the data you have at hand:
#
8 #   transaction_user_ids: a file that contains the user_id associated with each transaction 1..10_000_000
#   transaction_amounts:  a file that contains the amount transferred for each transaction 1..10_000_000
#   target_user_id:       a variable containing the user_id of a person-of-interest, under investigation.

12 # In each solution, the variables target_user_id, transaction_user_ids, and
#     transaction_amounts will be available.
#
# Use these variables in addition to the methods shown in the handout in order
16 #     to solve each question.

here_we_go!

20 # QUESTION ONE
#   Task:
#       Return the total number of transactions triggered by the target user.
answer_for question: 1, is: ->(target_user_id, transaction_user_ids, transaction_amounts){
24   your_solution_here!
}

# QUESTION TWO
28 #   Task:
#       Return the total number of deposits triggered by the target user.
#       Deposits are transactions that have a positive value.
answer_for question: 2, is: ->(target_user_id, transaction_user_ids, transaction_amounts){
32   your_solution_here!
}

```

```

# QUESTION THREE
36 # Task:
# Return the target user's total change in balance over the recorded period.
answer_for question: 3, is: -(target_user_id, transaction_user_ids, transaction_amounts){
  your_solution_here!
40 }

# QUESTION FOUR
# Task:
44 # Return the target user's total magnitude of even-valued withdrawals over the recorded period,
# WITHDRAWALS WHERE THE AMOUNT WITHDRAWN IS EVEN.
# Withdrawals are transactions with value below 0.
answer_for question: 4, is: -(target_user_id, transaction_user_ids, transaction_amounts){
48   your_solution_here!
}

# QUESTION FIVE
52 # Task:
# Return the number of times that someone with a multiple-of-222 user-id (0 inclusive) has deposited
# a multiple-of-222 (0 exclusive since deposit).
# Deposits are transactions with value above 0.
56 answer_for question: 5, is: -(target_user_id, transaction_user_ids, transaction_amounts) {
  your_solution_here!
}

60 tasks_complete!

```

Listing 5.5: Sample answers to the questions given.

```

require_relative './evaluation/user_test.rb'

here_we_go!
4 answer_for question: 1, is: ->(target_user_id, transaction_user_ids, transaction_amounts){
    transaction_user_ids[Int].count(target_user_id)
}
answer_for question: 2, is: ->(target_user_id, transaction_user_ids, transaction_amounts){
8   transaction_user_ids[Int].zip(transaction_amounts)
        .count { |id, amount| id == target_user_id && amount > 0 }
}
answer_for question: 3, is: ->(target_user_id, transaction_user_ids, transaction_amounts){
12  transaction_user_ids[Int].zip(transaction_amounts)
        .select { |id, amount| id == target_user_id }
        .snds
        .sum
16 }
answer_for question: 4, is: ->(target_user_id, transaction_user_ids, transaction_amounts){
    transaction_user_ids[Int].zip(transaction_amounts)
        .select { |id, amount| id == target_user_id && amount < 0 && amount.even? }
20        .snds
        .sum
}
answer_for question: 5, is: ->(target_user_id, transaction_user_ids, transaction_amounts) {
24  transaction_user_ids[Int].zip(transaction_amounts)
        .select { |id, amount| id % 222 == 0 }
        .select { |id, amount| amount % 222 == 0 && amount > 0 }
        .count
28 }
tasks_complete!

```


Chapter 6

Results

6.1 Benchmarks

6.1.1 Map tasks

6.1.1.1 Integer performance

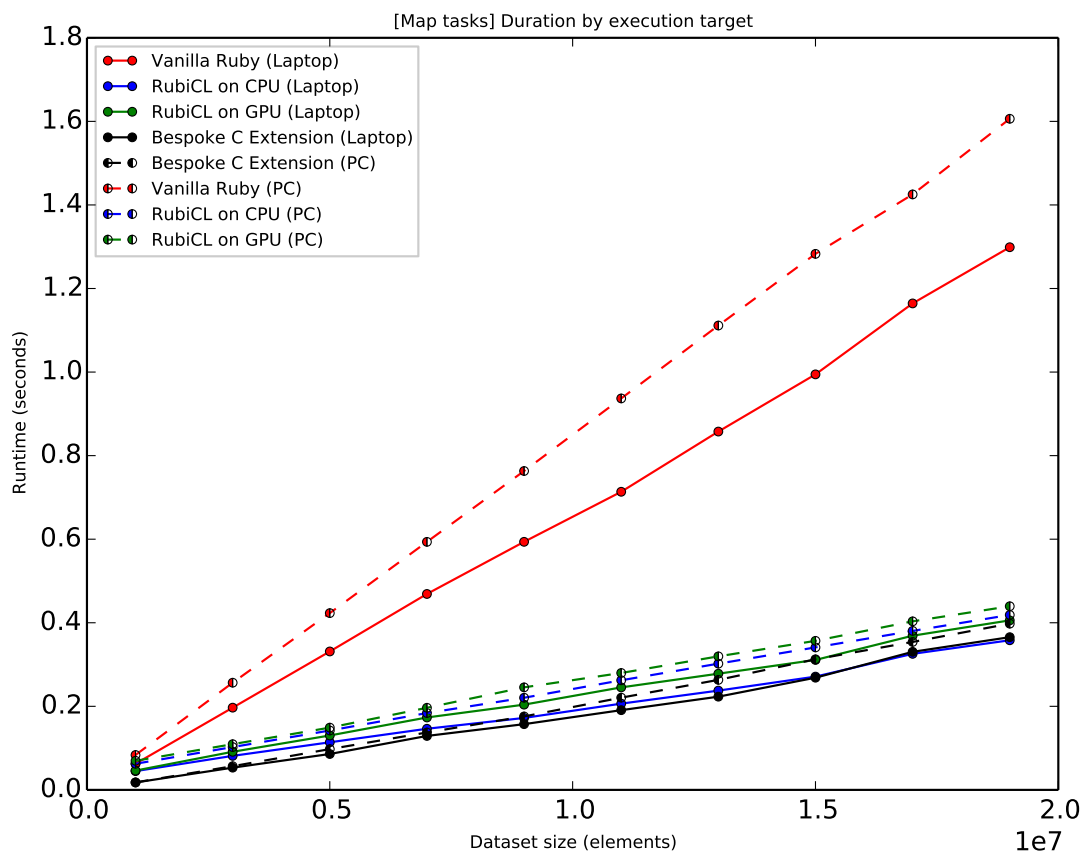


Figure 6.1: Task duration by execution target for *Map*.

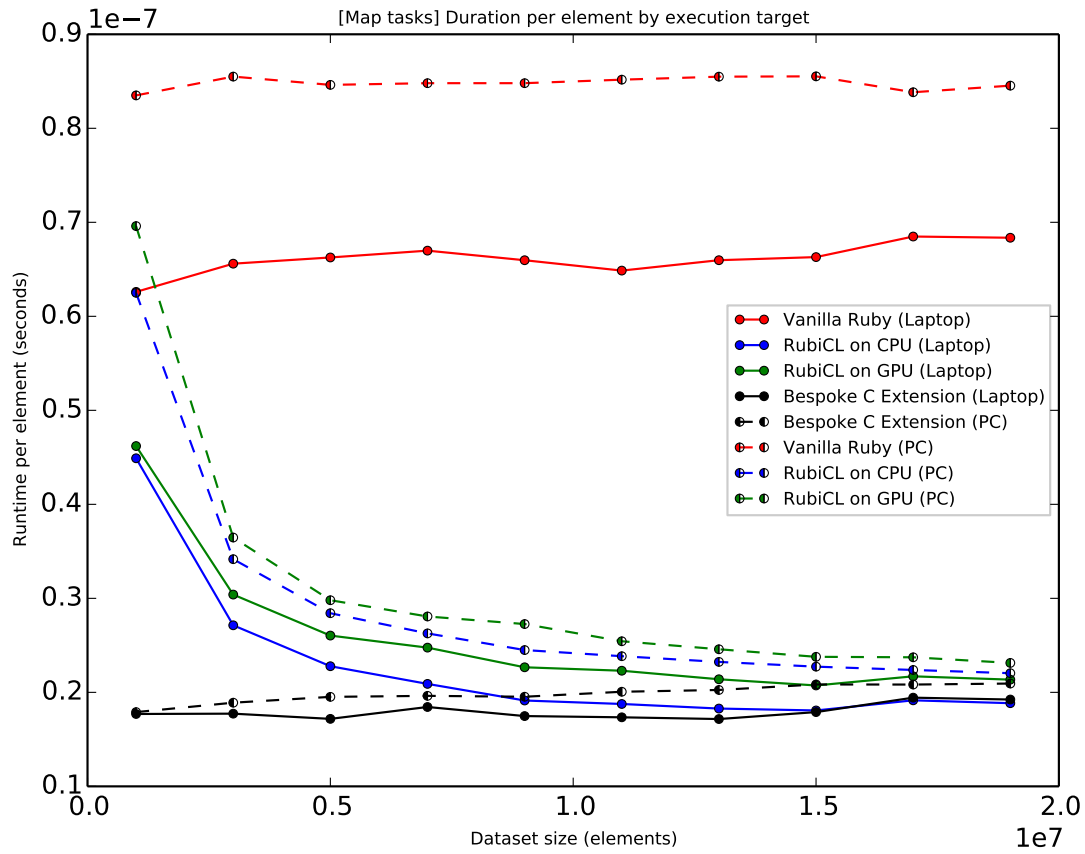


Figure 6.2: Task duration per processed element for *Map*.

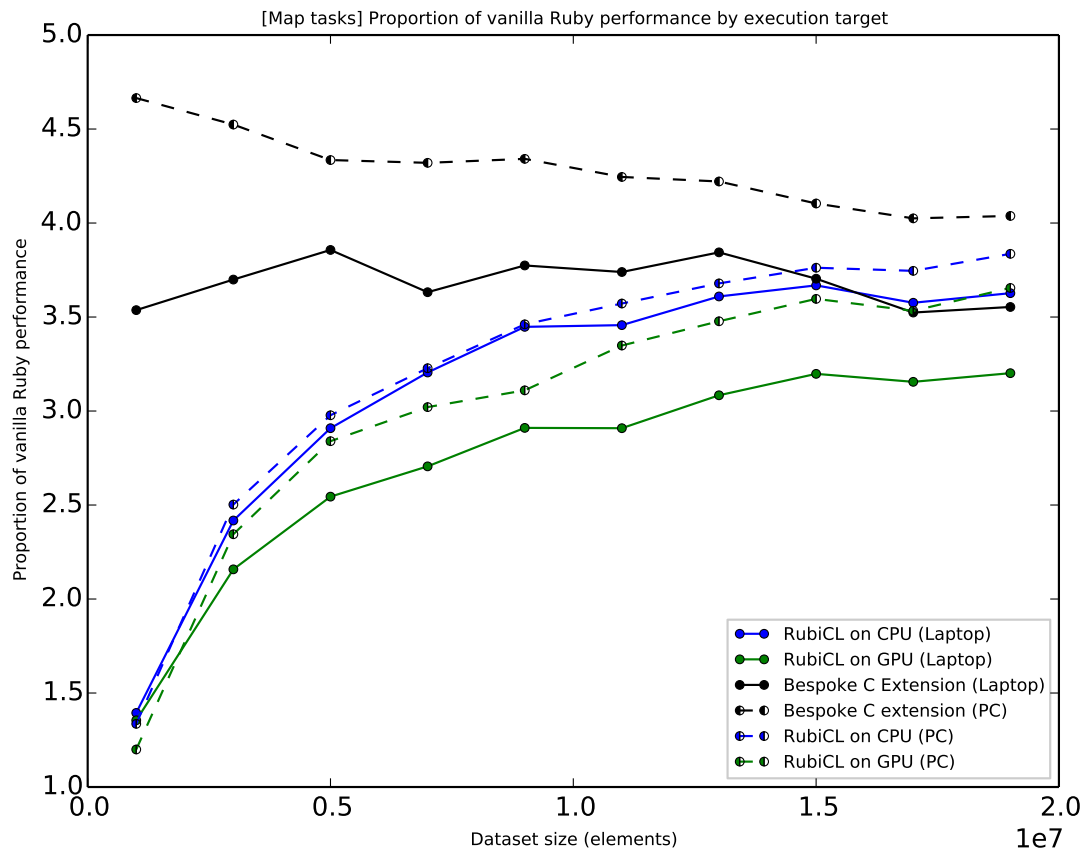


Figure 6.3: Proportion of vanilla Ruby performance achieved for *Map*.

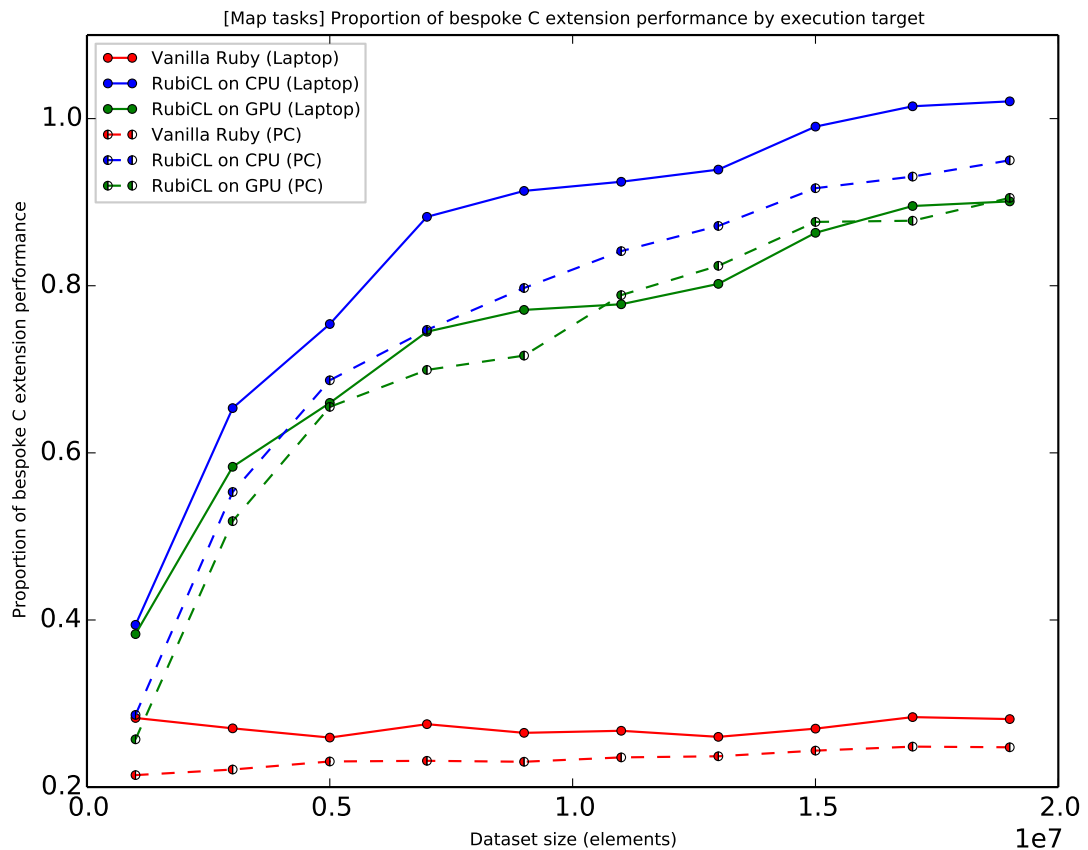


Figure 6.4: Proportion of bespoke C extension performance achieved for *Map*.

Recap of operation performed The *Map* task performed was the equivalent of `#map { |x| x + 1 }`. This has the effect of incrementing every member of the input dataset. Performing little work in the supplied function body produces a worst-case evaluation of library performance. This is because performing more work will allow increased throughput to mask any increased latency that the system has. Many tasks will be more involved than incrementation, and very few less so. A result showing that the library is beneficial here should apply even more to tasks that are of greater intensity.

Observations and analysis Figure 6.1 shows that all trialed alternatives exhibit similar performance when executing *Map* tasks. This is likely due to the computational simplicity of the task. The probable cause for the bottleneck is the need to move data in and out of the RubyVM's internal array structures. Although the gap is slight, the CPU compute-devices installed in both machines outperform the GPUs over the range of tested datasets. This is easiest to observe in Figure 6.2.

When parallelising purely-map tasks, the project library performs favourably compared to the standard `Enumerable#map` implementation of Ruby 2.2. Figure 6.3 demonstrates that, at best, a factor 3.5–4 speed-up over typical execution can be achieved on both systems. The figure also shows that for all tested datasets, the smallest of which contained 1 million elements, outsourcing computation to the library was beneficial.

In Figure 6.4, it can be seen that on both systems RubiCL throughput is not far from bespoke

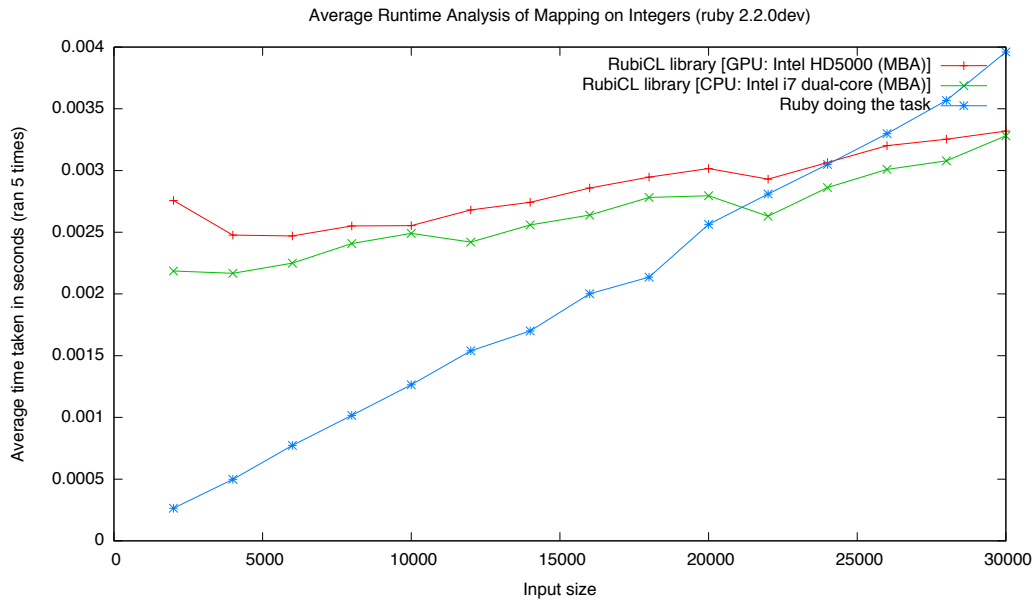


Figure 6.5: Duration for smaller-scale *Map* tasks.

sequential code. On the laptop, the parallel CPU implementation exceeds the non-parallel native extension. It achieves 1.02 times the rate of processing on 19 million elements. However, while the laptop CPU presents 4 hardware threads to OpenCL, the native extension utilises only a single thread of execution. As both implementations are performing roughly the same number of operations, it appears that OpenCL’s raw throughput increase is insignificant after the processing-model overhead is accounted for.

It is clear that the throughput with which Ruby is capable of performing *Map* tasks has been significantly increased. On the other hand, the project’s parallel library does not significantly outperform a custom, tailored, sequential solution. Yet, for all systems choosing the optimal device, no less than 80% of the best-presented throughput is achieved at 10 million elements, improving to no less than 95% at 19 million. With the library providing automatic translation of all functions stated into parallel execution patterns, this deficit is insignificant. Much more significant is the mitigation of the need to write and compile native extensions for every required calculation.

Smaller scale Map tasks Figure 6.5 shows that the RubiCL library, when executing on the laptop system, is beneficial for *Map* tasks containing greater than 20,000–25,000 elements. It also demonstrates that the laptop system experiences task latency of around 20ms.

6.1.1.2 Floating-point performance

Figure 6.7 shows that the lower-bound for beneficial *Map* acceleration by the RubiCL library remains roughly the same for floating-point datasets as what was observed for integer datasets.

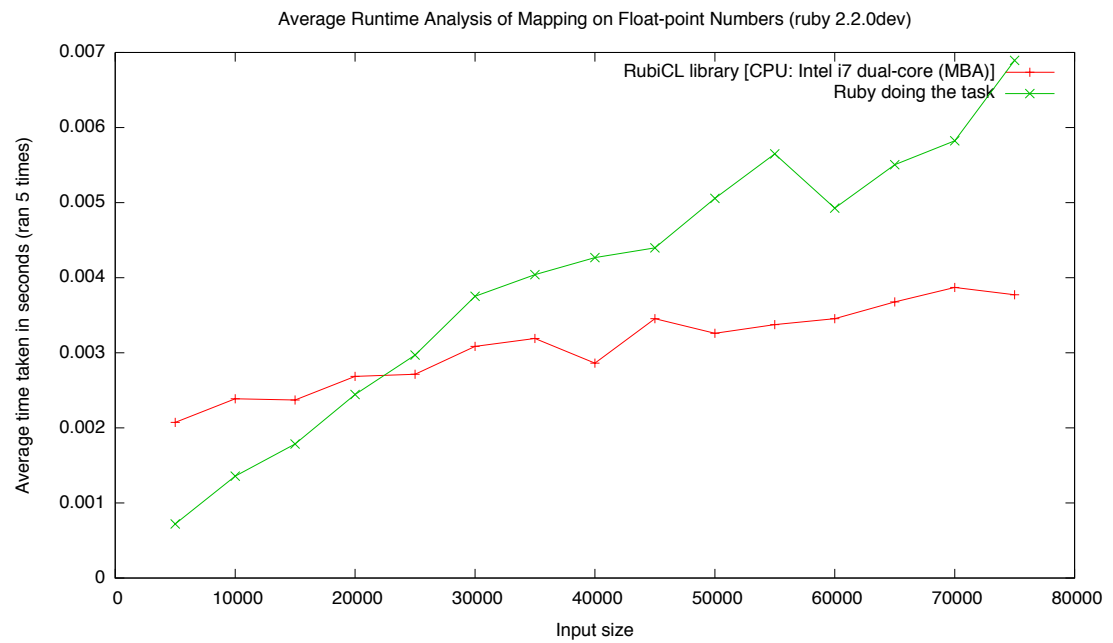


Figure 6.6: Duration for smaller-scale *Map* tasks on floating-point numbers

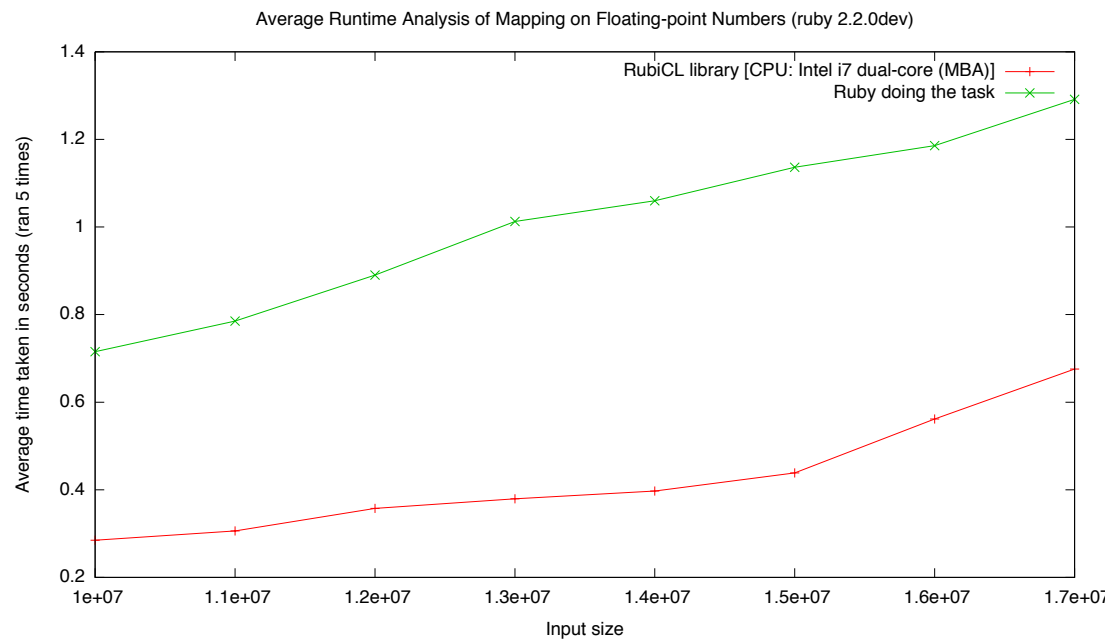


Figure 6.7: Duration for larger-scale *Map* tasks on floating-point numbers

Again, comparing OpenCL execution on the CPU to standard Ruby, it is worth outsourcing computation above 20,000 elements.

The RubiCL library offers a speed-up of around 2 times the traditional implementation. The reduction over integer speed-up is likely due to object conversion no longer occurring in parallel, and the linear dereference cost added to both implementations.

6.1.2 Dense Filter tasks

6.1.2.1 Integer performance

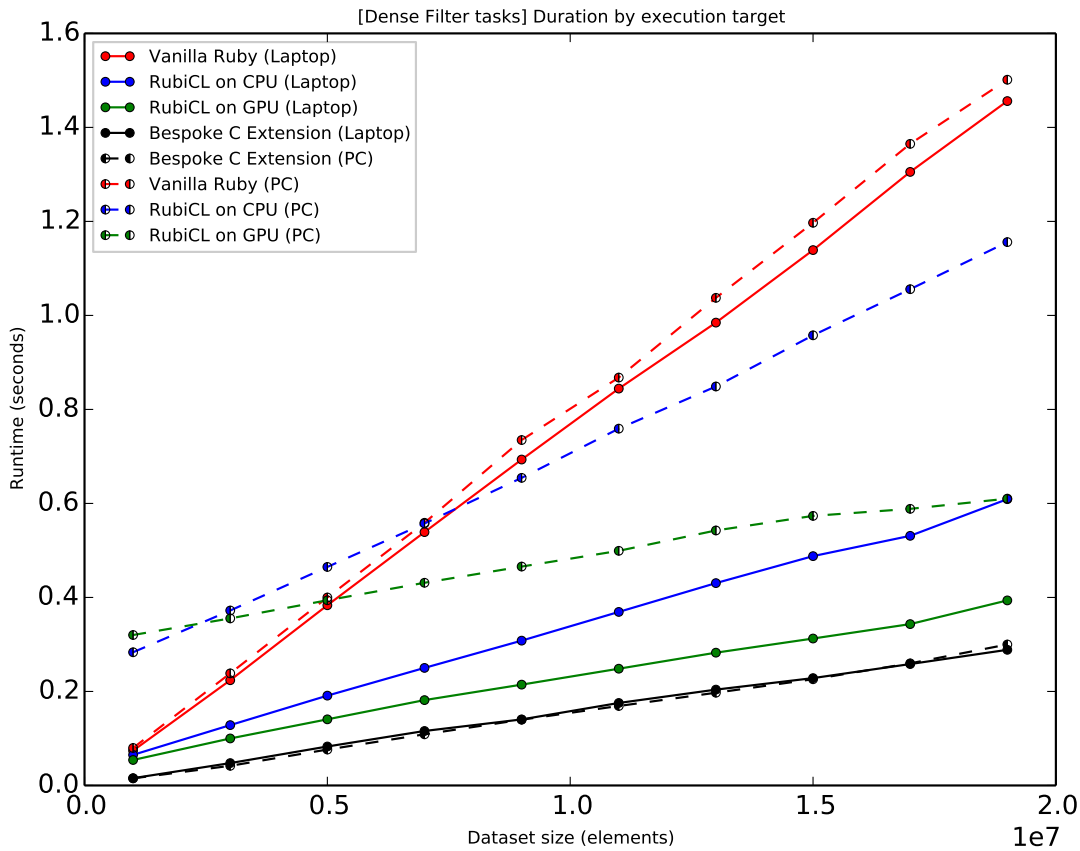


Figure 6.8: Task duration by execution target for dense *Filter*.

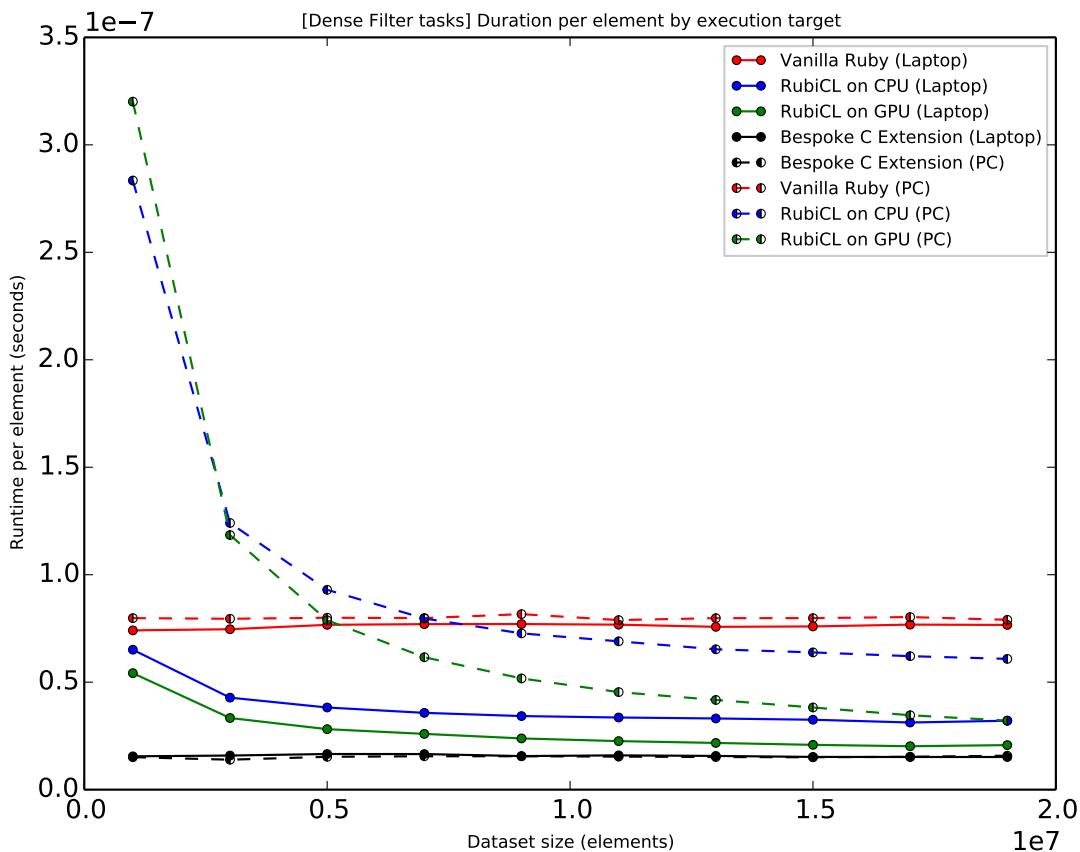


Figure 6.9: Task duration per processed element for dense *Filter*.

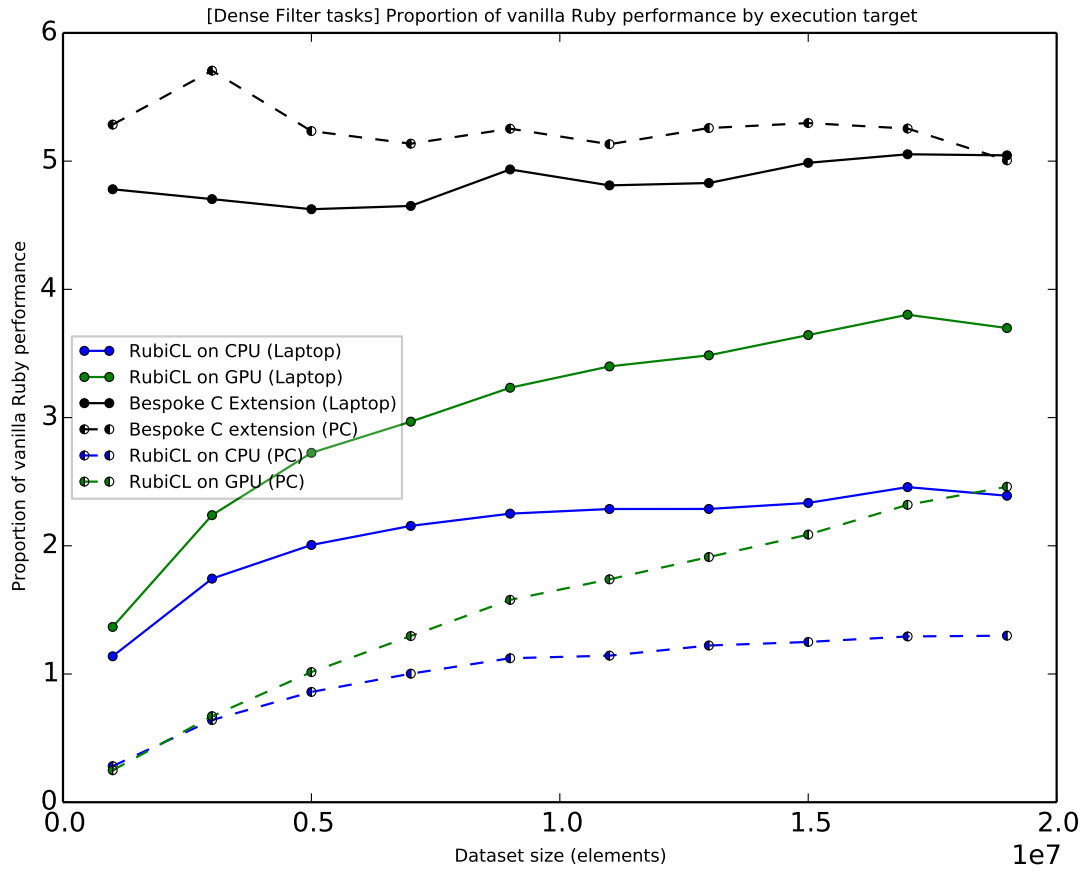


Figure 6.10: Proportion of vanilla Ruby performance achieved for dense *Filter*.

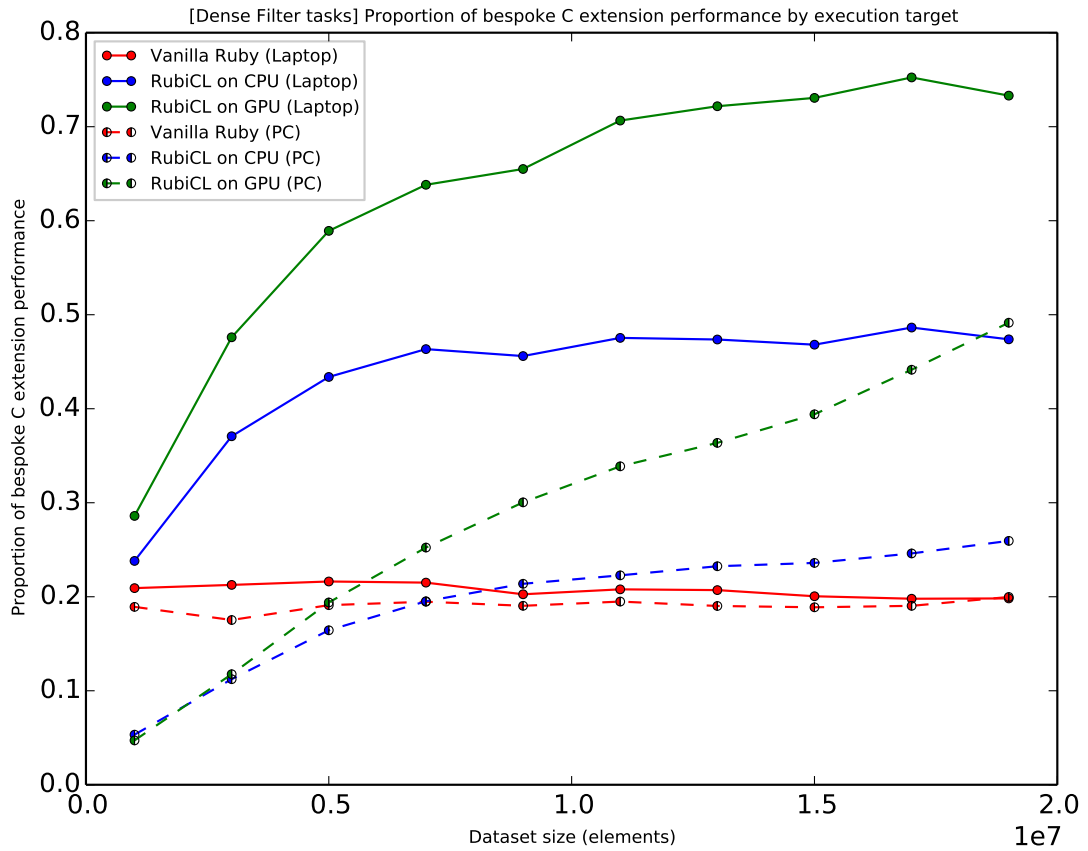


Figure 6.11: Proportion of bespoke C extension performance achieved for dense *Filter*.

Recap of operation performed The dense *Filter* task performed was the equivalent of `#select { |x| x.even? }`. With the ascending range of data supplied, this will return a subset of the input dataset with half the number of elements remaining.

Observations and analysis Figure 6.8 is less cluttered than the corresponding graph for *Map* tasks, as there is more variation between the performance of dense *Filter* implementations. The figure suggests that *Filter* tasks scheduled on the desktop system suffer from a higher latency than their counterparts on the laptop. This is signified by the comparatively elevated run-times for smaller datasets.

Further unlike *Map* tasks, on both systems the GPU compute-devices outperform the CPU when filtering large datasets. For the laptop system, the domination is present on every tested dataset size. On the contrary, the desktop CPU is initially a shade faster but is quickly dwarfed by the significantly higher throughput of the GPU device.

On the laptop system, Figure 6.10 demonstrates that the library is beneficial when processing all datasets within the tested range. The desktop is not quite as successful at performing dense purely-*Filter* tasks, hampered when producing subsets of smaller datasets by its increased latency. At least 5 million elements are required before it is worthwhile to offload computation onto the GPU via RubiCL. The CPU trails not long after, at 8 million elements, but never achieves more than 25% speed-up over the standard Ruby implementation.

On both test systems, when using the GPU, a noticeable speed-up of *Filter* operations can be achieved. With a 2.5 times speed-up on the desktop and over 3.5 times on the laptop, large filtering operations are significantly accelerated by the RubiCL library.

Figure 6.11 shows that the laptop GPU achieves a high proportion, peaking at 75%, of bespoke sequential code performance. The desktop system boasts a lesser proportion, at 50%, but the lack of plateau in the figure suggests that this gap would close further as datasets increase in size.

The lacklustre performance when executing on CPU devices can be partly explained by the fact that the parallel implementation of filtering, although asymptotically identical in cost, requires much more work than a sequential filter. In this case, the hidden constants involved for distributing computation have a large effect on the task duration, larger than that of parallelising the predicate scan and index calculations along the data.

This reasoning can also explain why the GPU devices fail to outperform the custom extension over the given range of datasets. Nonetheless, the need to write and compile native extensions for each distinct query performed is again removed when using the RubiCL library. A system-dependent performance hit of between 25% and 50% behind a handwritten extension is far more justifiable when it facilitates rapid-prototyping, especially when compared to the 80% penalty that Figure 6.11 highlights for unoptimised Ruby 2.2.

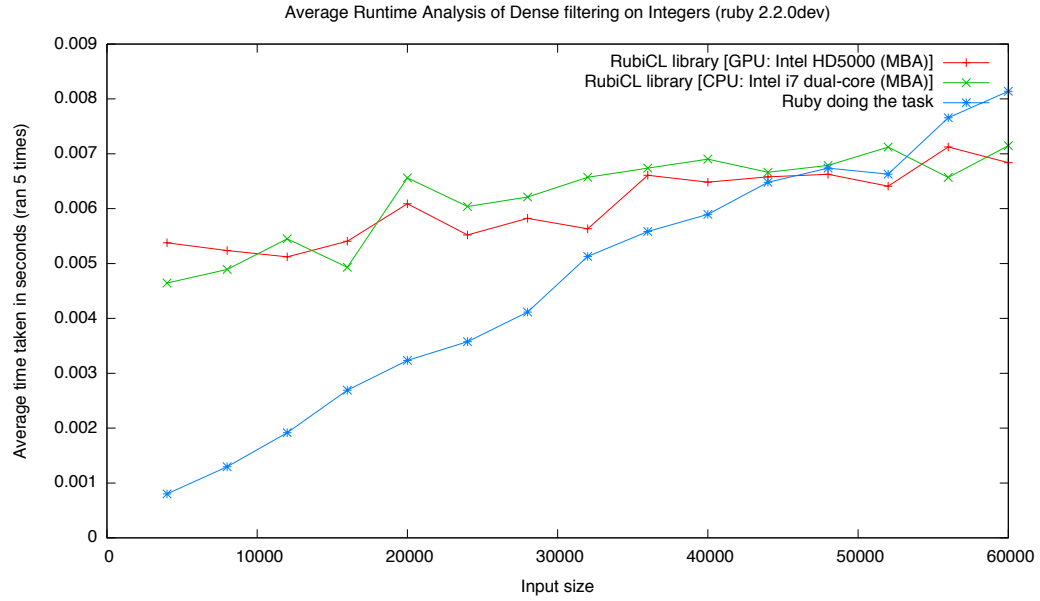


Figure 6.12: Duration for smaller-scale dense *Filter* tasks.

Smaller scale dense *Filter* tasks Figure 6.12 shows that the RubiCL library, when executing on the laptop system, is beneficial for dense *Filter* tasks containing greater than 50,000 elements. It also demonstrates that the laptop system experiences task latency of around 50ms.

6.1.2.2 Floating-point performance

Figure 6.13 shows that the lower-bound for beneficial dense *Filter* acceleration by the RubiCL library remains roughly the same for floating-point datasets as what was observed for integer datasets. Again, comparing OpenCL execution on the CPU to standard Ruby, it is worth outsourcing computation above 50,000 elements.

The RubiCL library offers a speed-up of around 2 times the traditional implementation. This is shown in Figure 6.14 and is nearly identical to the CPU speed-up achieved for integer datasets. This suggests that the added cost of object dereferencing and re-creation, necessary for all implementations, is insignificant compared to the work involved when performing a filtering operation.

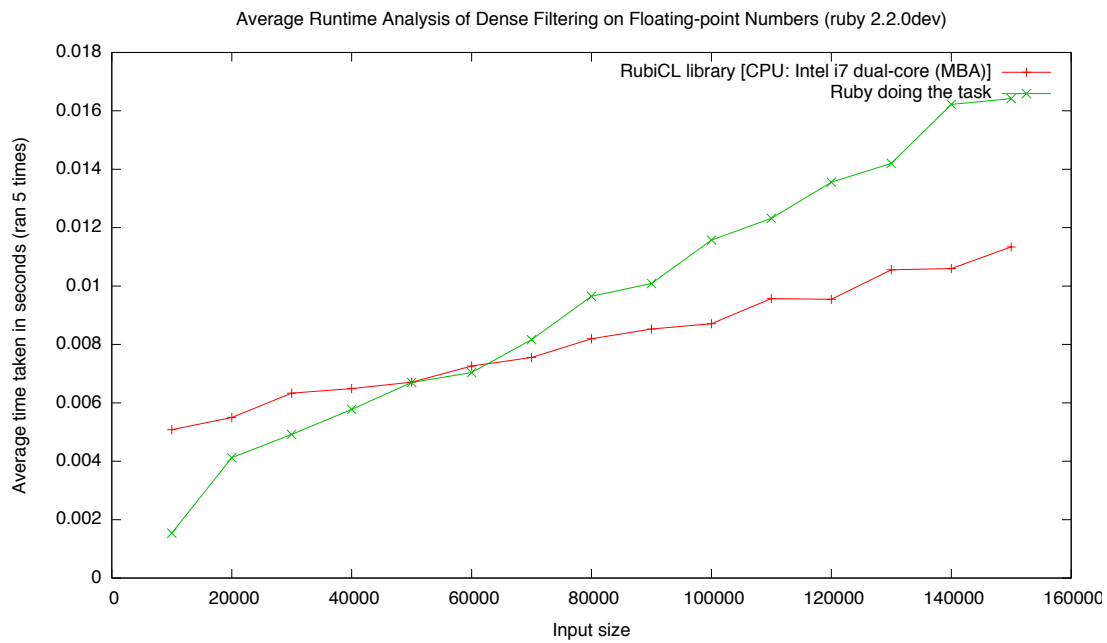


Figure 6.13: Duration for smaller-scale dense *Filter* tasks on floating-point numbers

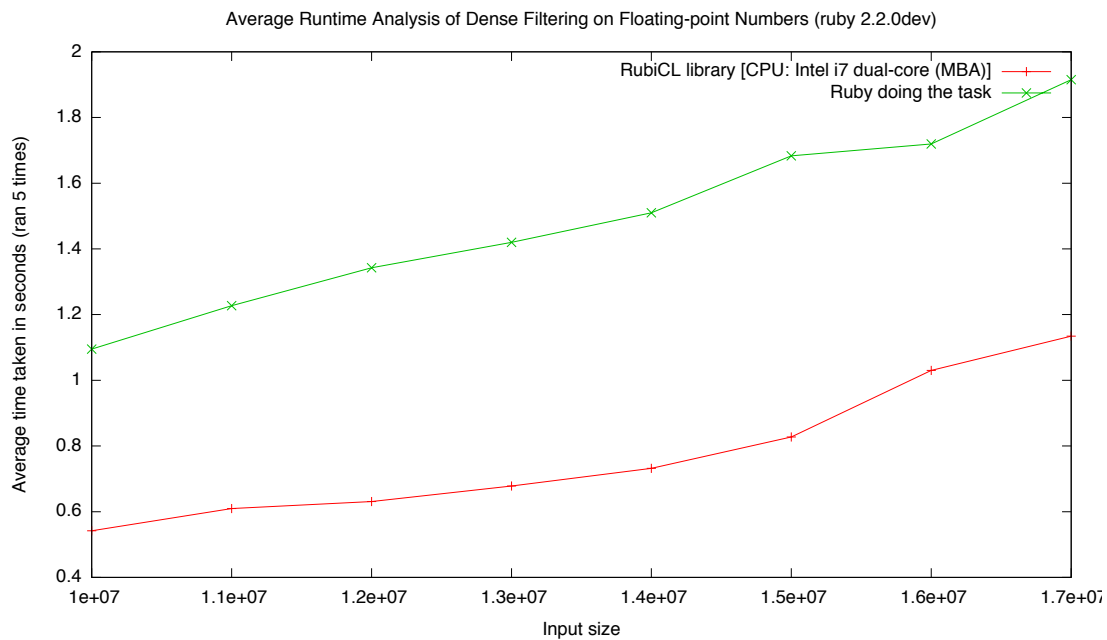


Figure 6.14: Duration for larger-scale dense *Filter* tasks on floating-point numbers

6.1.3 Sparse Filter tasks

6.1.3.1 Integer performance

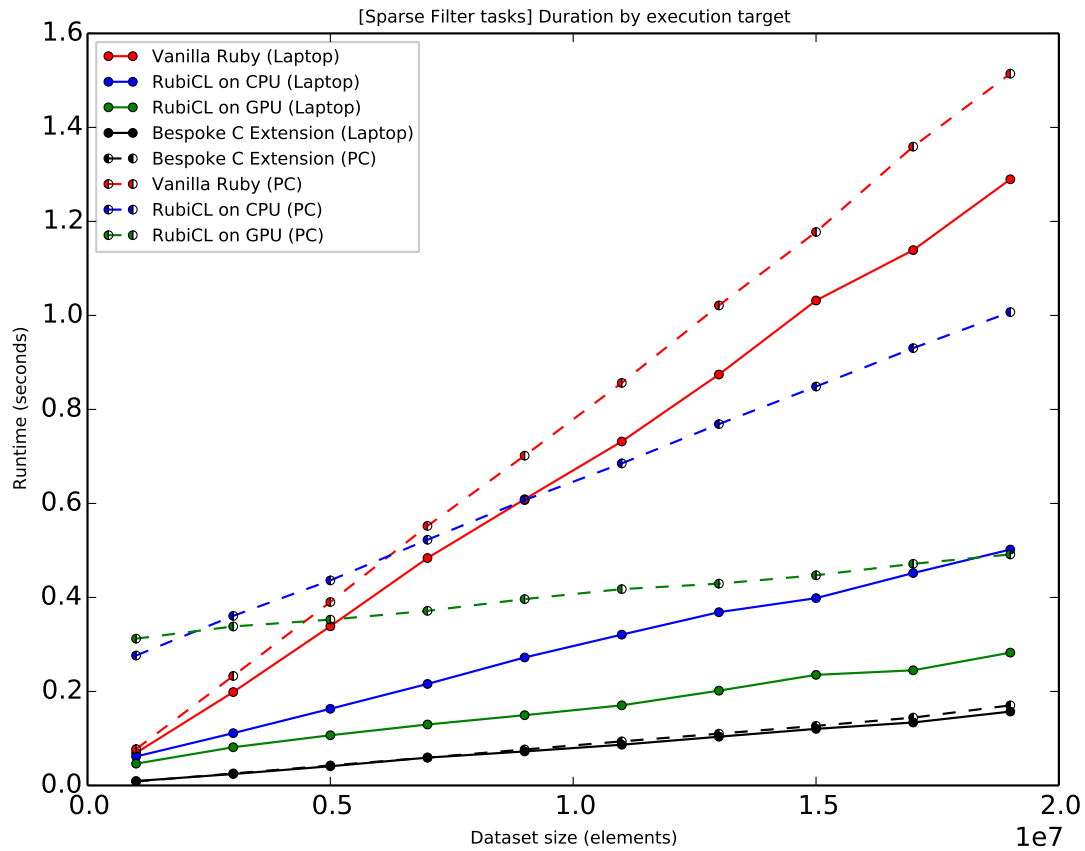


Figure 6.15: Task duration by execution target for sparse *Filter*.

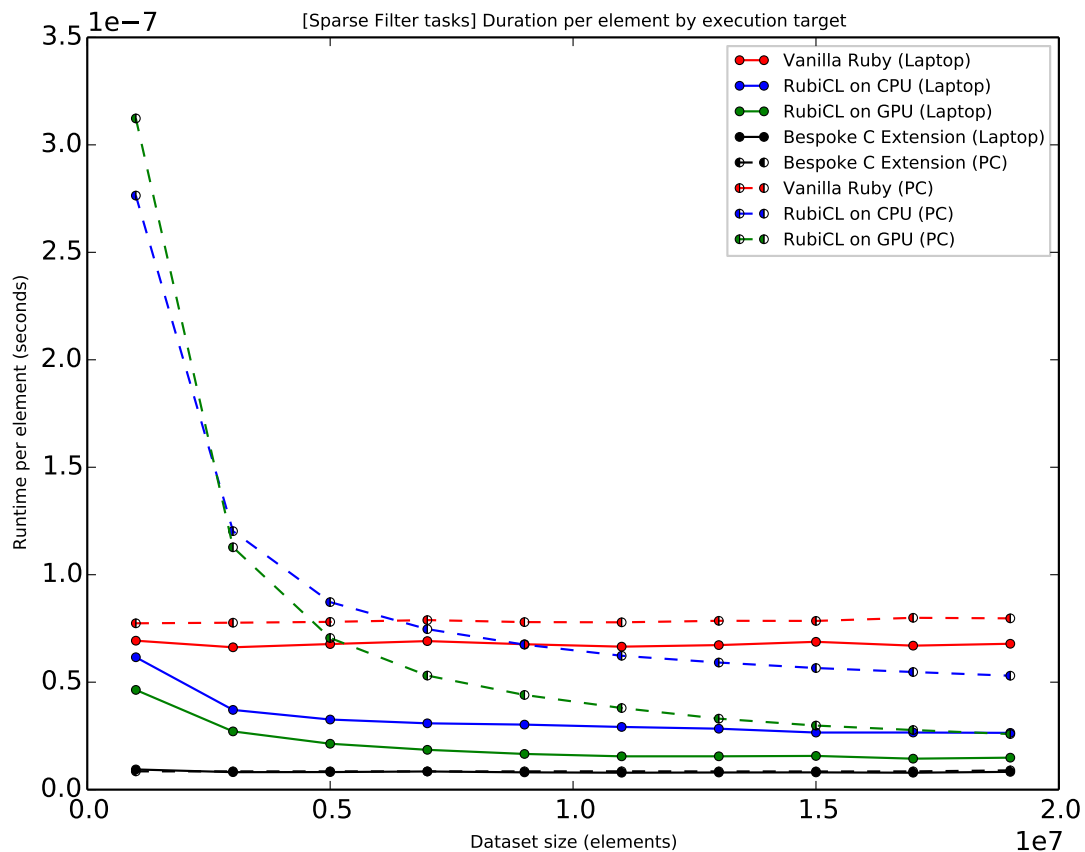


Figure 6.16: Task duration per processed element for sparse *Filter*.

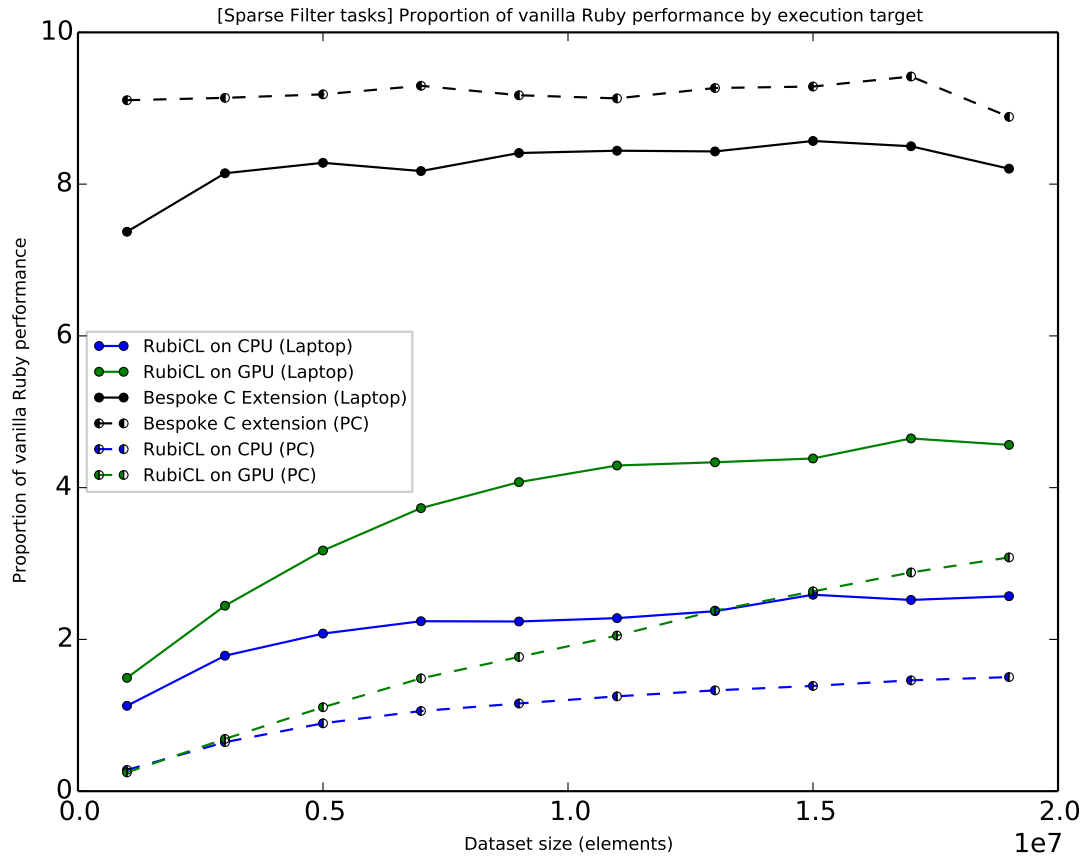


Figure 6.17: Proportion of vanilla Ruby performance achieved for sparse *Filter*.

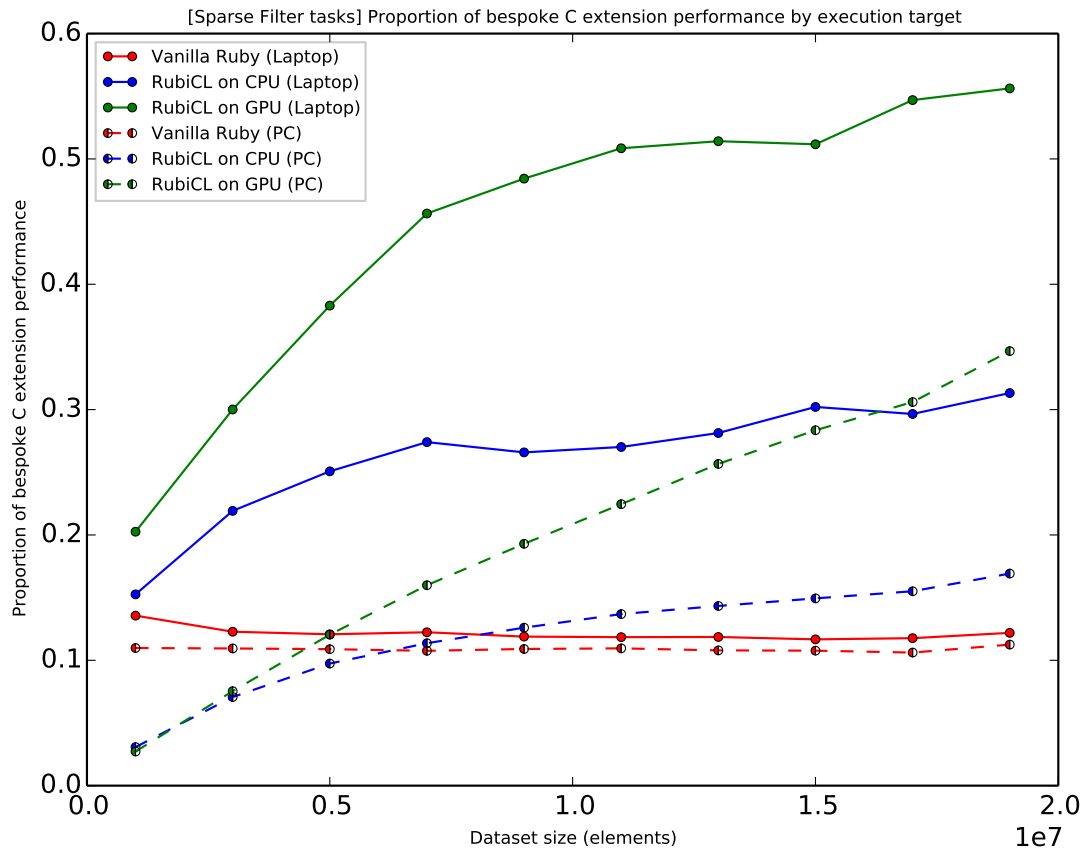


Figure 6.18: Proportion of bespoke C extension performance achieved for sparse *Filter*.

Recap of operation performed The sparse *Filter* task, returning fewer elements than the dense task, performed was the equivalent of `#select { |x| x % 20 == 0 }`. This selects all elements that are evenly divisible by 20. With the ascending range of data supplied, this will return a subset of the input dataset with 5% of its elements remaining.

Observations and analysis Figure 6.15 looks very similar to that of dense filtering. Indeed, many of the observations are the same. One reason for this is that none of the code benchmarked, including `Enumerable#select`, changes behaviour when datasets are sparse. Instead, the slight change in performance can be explained by differing proportions of time spent inserting elements or transferring device datasets when the set of returned results is smaller in size.

As before, the difference in latency between the laptop and desktop systems causes a significant proportional gap for smaller datasets. It leaves sparse *Filter* needing the same minimum dataset sizes for beneficial inclusion as dense *Filter*. This identical result is useful as it suggests that the threshold for parallelisation can be estimated without prior knowledge of the proportion of data retained.

Yet again, GPU devices are dominant among the OpenCL filtering implementations, for all but the smallest dataset on the desktop. Much like the previous graph for filtering, the desktop GPU does not appear to have plateaued in time-per-element. Therefore, further study should be performed to see at what size dataset this occurs.

The bespoke extension performs much better comparatively at sparse filtering than dense filtering. Figure 6.17 shows a 9 times performance speed-up over unoptimised code, nearly twice the speed-up of dense filtering. With this in mind, Figure 6.18 shows a decrease in performance of RubiCL relative to bespoke filtering, compared to the denser predicate examined earlier.

The inverse is true in Figure 6.17, with RubiCL demonstrating an improved 3–5 times speed-up when executing on GPU devices over Ruby 2.2 for dense filtering. The differences in relative performance between dense and sparse *Filter* task implementations suggest that the cause for diverging ratios may result from there being fewer conditional insertions to the result vector. Alternatively, when less data is returned from a compute-device, less time is spent, proportionally, in the comparatively slow operation of cross-device data transfer compared to the quick action of filtering itself.

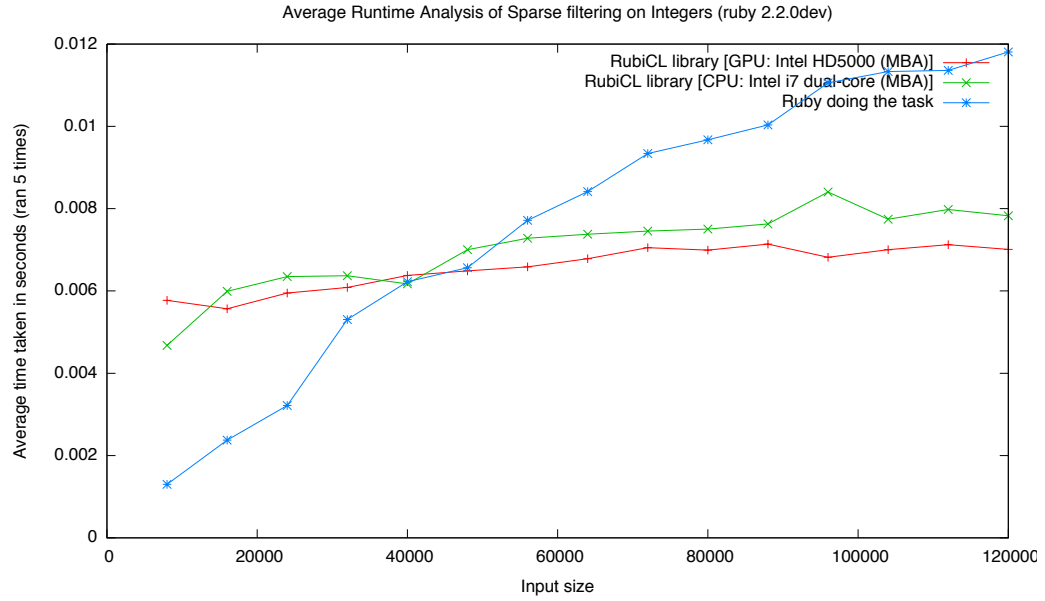


Figure 6.19: Duration for smaller-scale sparse *Filter* tasks.

Smaller scale sparse *Filter* tasks Figure 6.19 shows that the RubiCL library, when executing on the laptop system, is beneficial for sparse *Filter* tasks containing greater than 50,000 elements. This is identical to the dense *Filter* cutoff. It also demonstrates that the laptop system experiences task latency of around 50ms.

6.1.3.2 Floating-point performance

Figure 6.20 shows that the lower-bound for beneficial sparse *Filter* acceleration by the RubiCL library remains roughly the same for floating-point datasets as what was observed for integer datasets. Again, comparing OpenCL execution on the CPU to standard Ruby, it is worth outsourcing computation above 50,000 elements.

Figure 6.21 demonstrates that the RubiCL library offers a speed-up of around 2 times the traditional implementation. Again, this is nearly identical to the CPU speed-up achieved for integer datasets and suggests that the added cost of object dereferencing and re-creation, necessary for all implementations, is insignificant compared to the work involved when performing a filtering operation.

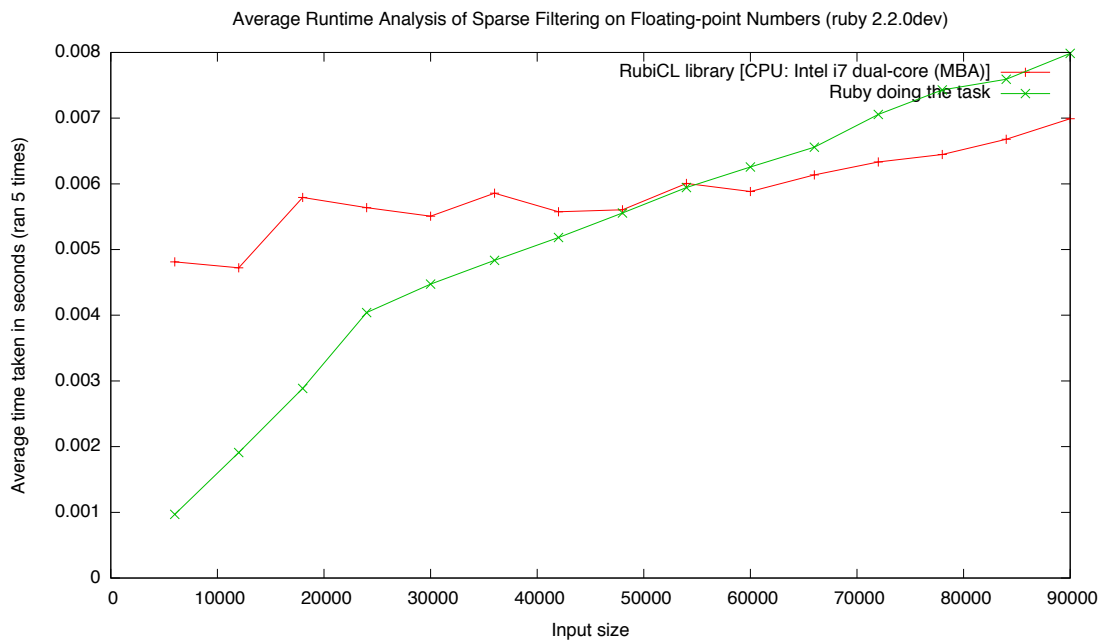


Figure 6.20: Duration for smaller-scale sparse *Filter* tasks on floating-point numbers

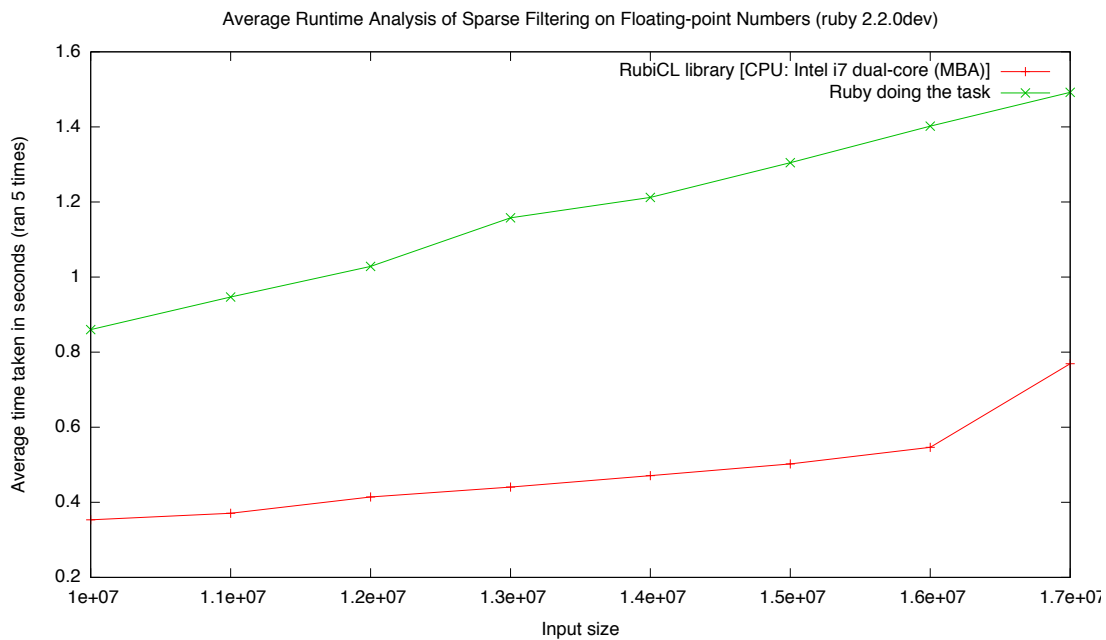


Figure 6.21: Duration for larger-scale sparse *Filter* tasks on floating-point numbers

6.1.4 MapFilter tasks

6.1.4.1 Integer performance

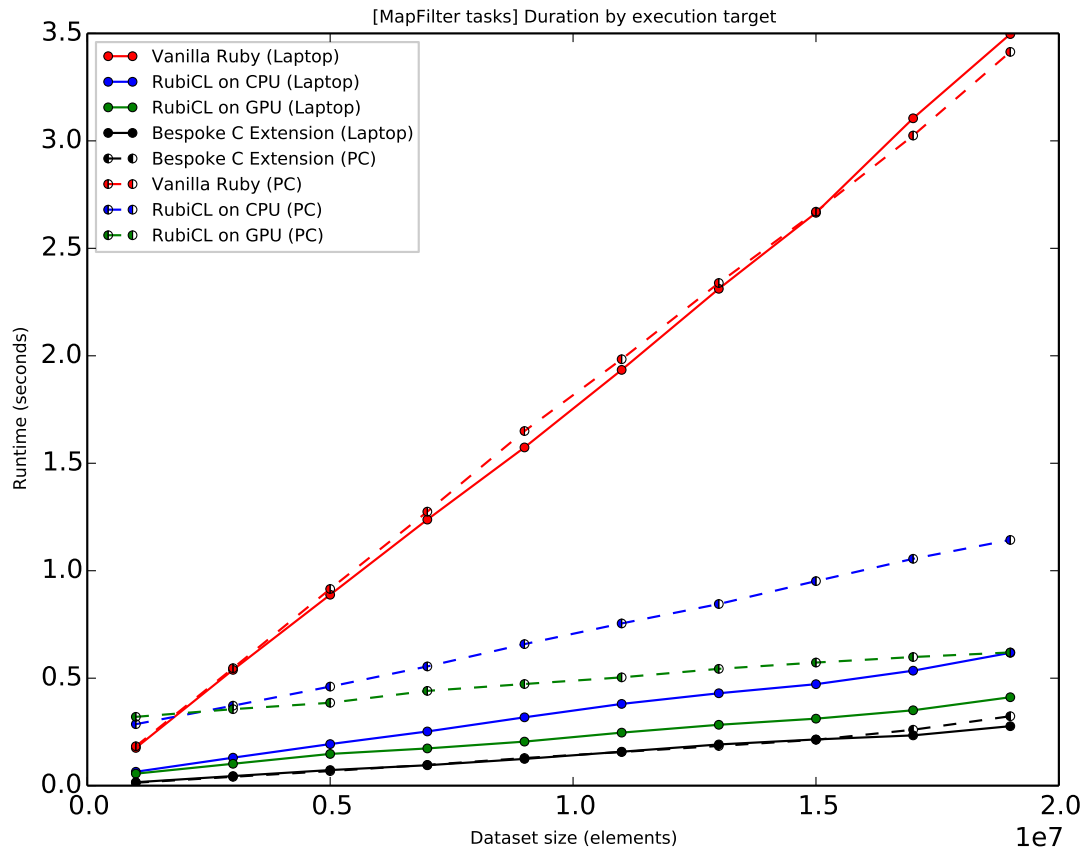


Figure 6.22: Task duration by execution target for *MapFilter*.

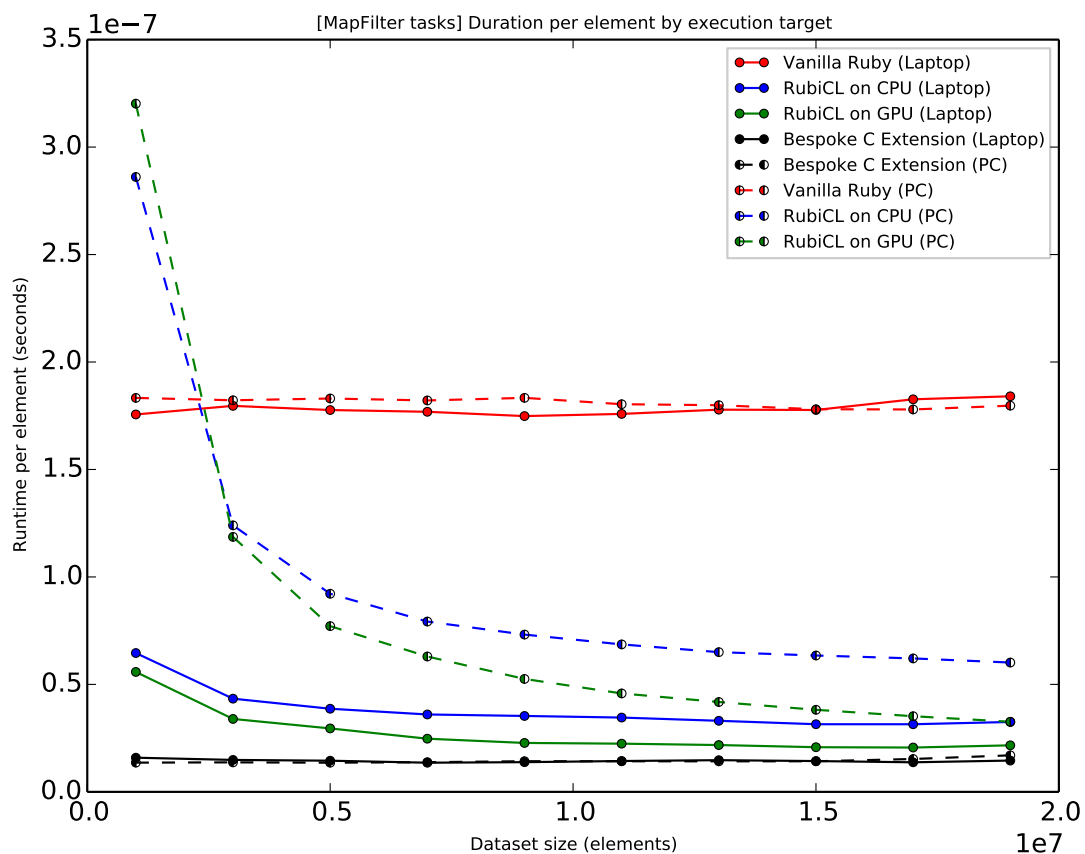


Figure 6.23: Task duration per processed element for *MapFilter*.

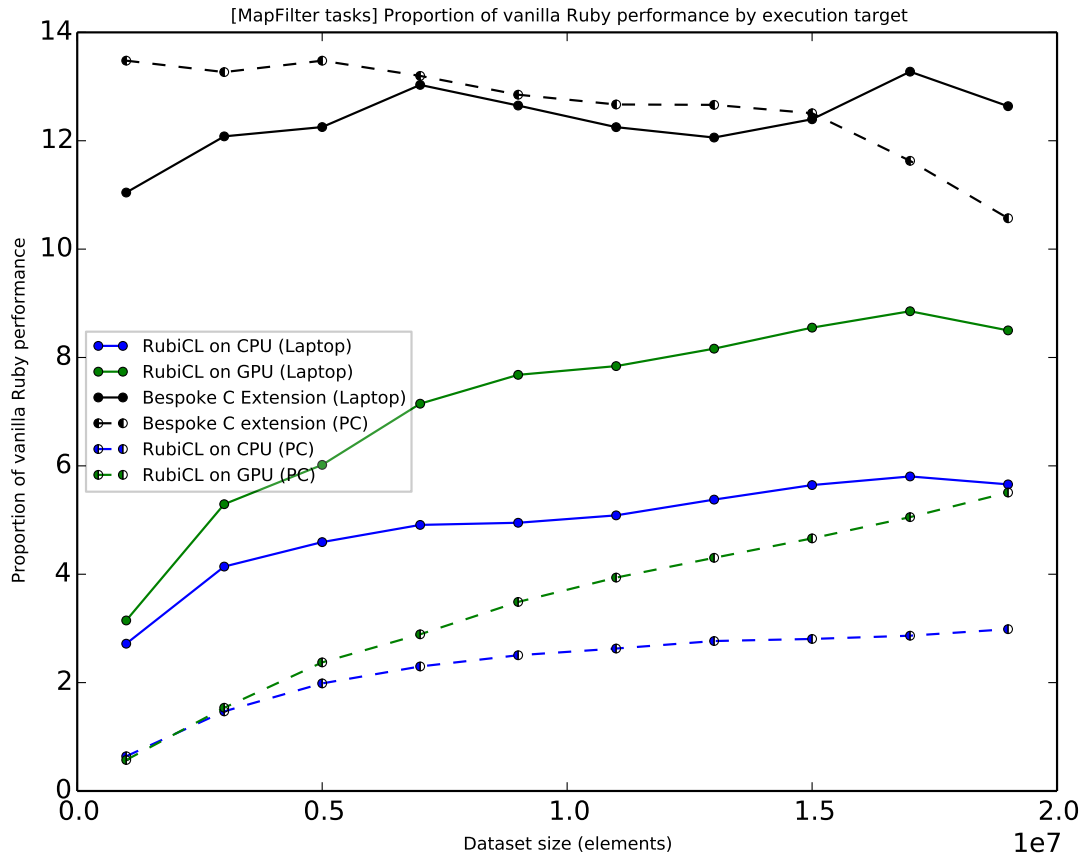


Figure 6.24: Proportion of vanilla Ruby performance achieved for *MapFilter*.

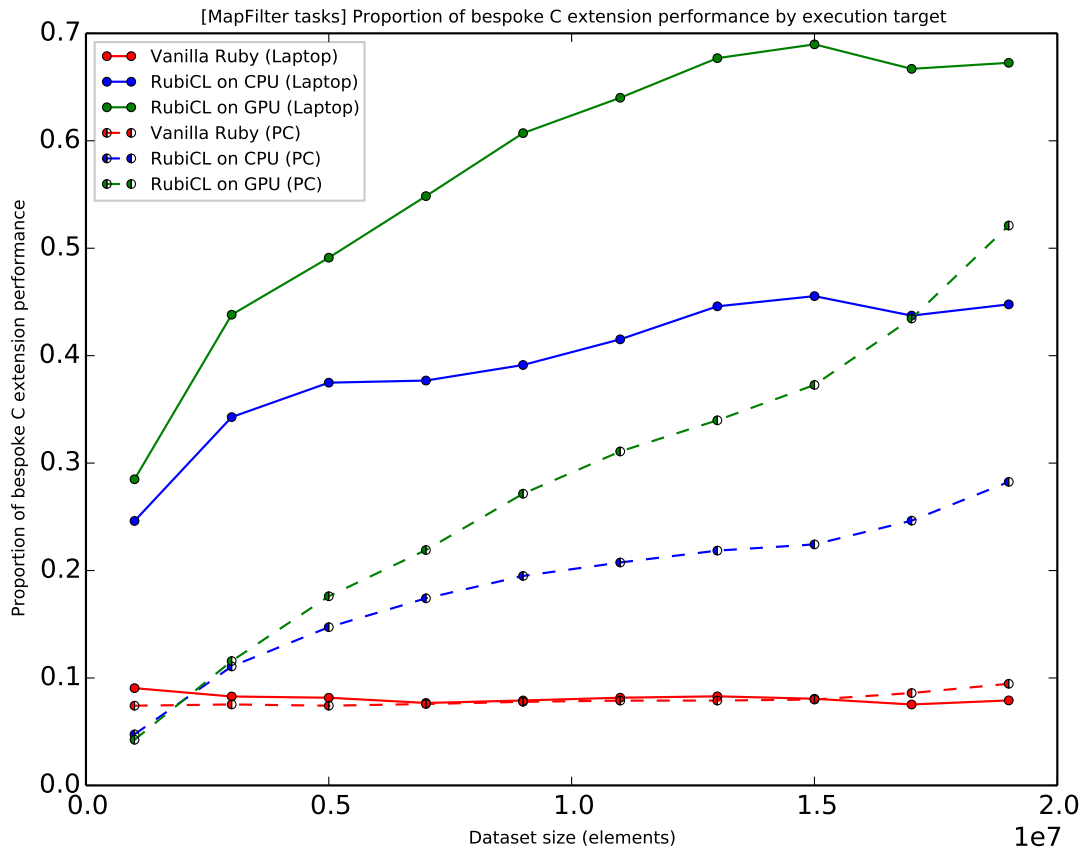


Figure 6.25: Proportion of bespoke C extension performance achieved for *MapFilter*.

Recap of operation performed The computation pipeline for this benchmark consisted of the earlier *Map* task, immediately followed by the dense *Filter* task. This has the combined effect of incrementing all elements and then returning the subset of mutated elements that are even. Again this returns a dataset that is half of the original size. Furthermore, the tasks can undergo *fusion* in order to reduce the number of kernels scheduled and required passes over the data.

Observations and analysis When a *Map* task is followed by a *Filter* task, the project's task fusion optimisation drastically improves performance. Figure 6.22 demonstrates how significantly run-time diverges, with the gap between Ruby 2.2 and competing implementations expanding greatly as larger datasets are introduced. The need for multiple passes over the data greatly delays the unoptimised code, as intermediate yet discarded results for the method pipeline are computed. The optimisation can be seen to reduce the minimum dataset length required for RubiCL's desktop parallelism to provide performance gains over the standard implementation, shown in Figure 6.24. At just 2 million elements, it is less than half of that required when filtering alone.

Figure 6.24 also demonstrates the significant throughput increases provided by RubiCL, compared to the standard library. At over 8 times speed-up, combining subsequent *Map* and *Filter* tasks then dispatching the computation to the GPU can speed up laptop computation greatly. At nearly 5 times speed-up, and the proportional graph again showing no sign of plateau, the same tactic is also highly beneficial on the desktop system used for testing.

GPU devices continue to dominate CPU devices, as with other *Filter* tasks. This occurs even though a *Map* task, something that CPU architecture excelled at earlier, has been prepended. It is possible that the simpler task performed earlier did not benefit from the improved device throughput, once the latency cost of context-switching computation was introduced.

Comparison with a bespoke sequential solution in Figure 6.25 shows that a large proportion of tailored solution performance is obtained on both systems. The laptop system obtains, at best, 70% performance and the desktop system obtains 50% with further indications of increasing proportion on larger datasets. This is even more significant as the manual fusion process of custom extension development is conceptually more involved than transcribing distinct tasks. As more mutation and filtering conditionals are brought into the loop body, the compiler is able to eradicate more redundant computation but the source code becomes harder to interpret correctly. With RubiCL's task fusion, separately stated pipeline stages are less concept-dense and therefore easier to understand.

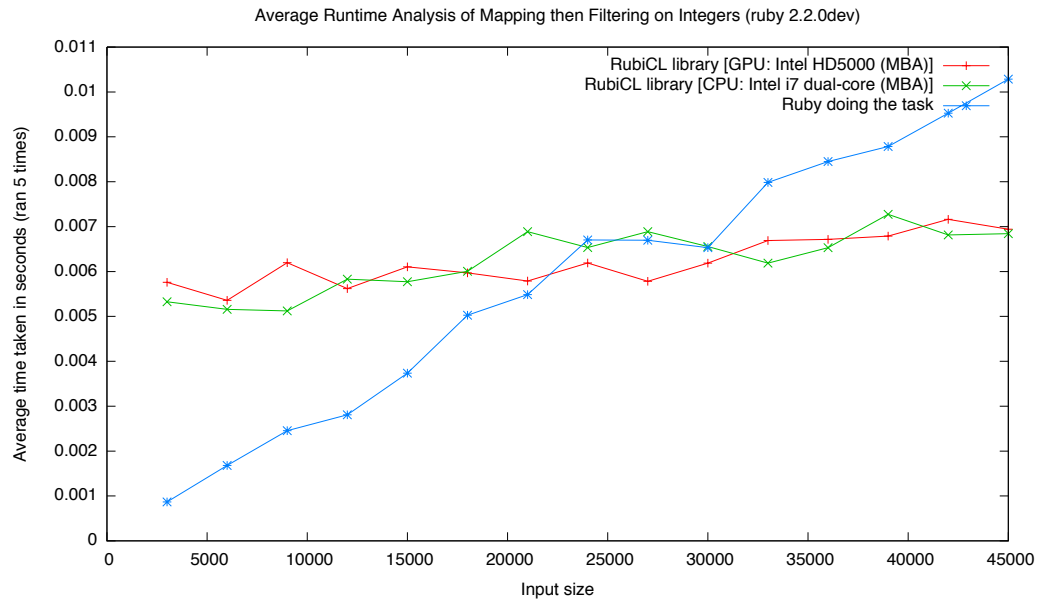


Figure 6.26: Duration for smaller-scale *MapFilter* tasks.

Smaller scale *MapFilter* tasks Figure 6.26 shows that the RubiCL library, when executing on the laptop system, is beneficial for sparse *MapFilter* tasks containing greater than 25,000–30,000 elements. It also demonstrates that the laptop system experiences task latency of around 50ms.

6.1.4.2 Floating-point performance

Figure 6.27 shows that the lower-bound for beneficial *MapFilter* acceleration by the RubiCL library remains roughly the same for floating-point datasets as what was observed for integer datasets. Comparing OpenCL execution on the CPU to standard Ruby, it is worth outsourcing computation above 20,000 elements, shown in Figure 6.28.

The RubiCL library offers a speed-up of around 3–4 times the traditional implementation. This is nearly identical to the CPU speed-up achieved for integer datasets and again suggests that the added cost of object dereferencing and re-creation is insignificant.

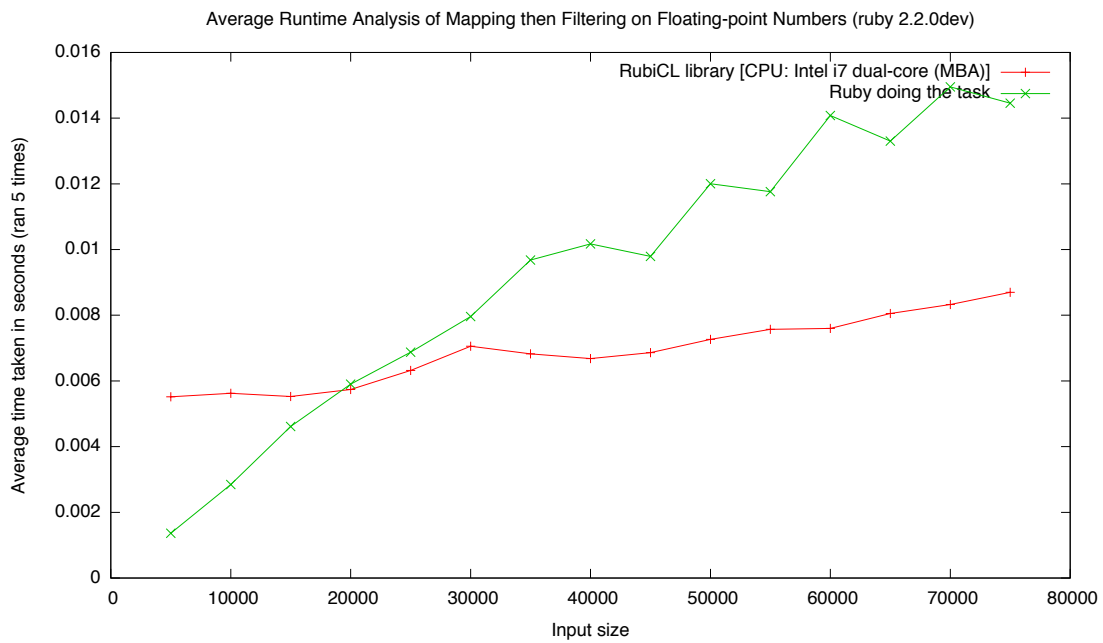


Figure 6.27: Duration for smaller-scale *MapFilter* tasks on floating-point numbers

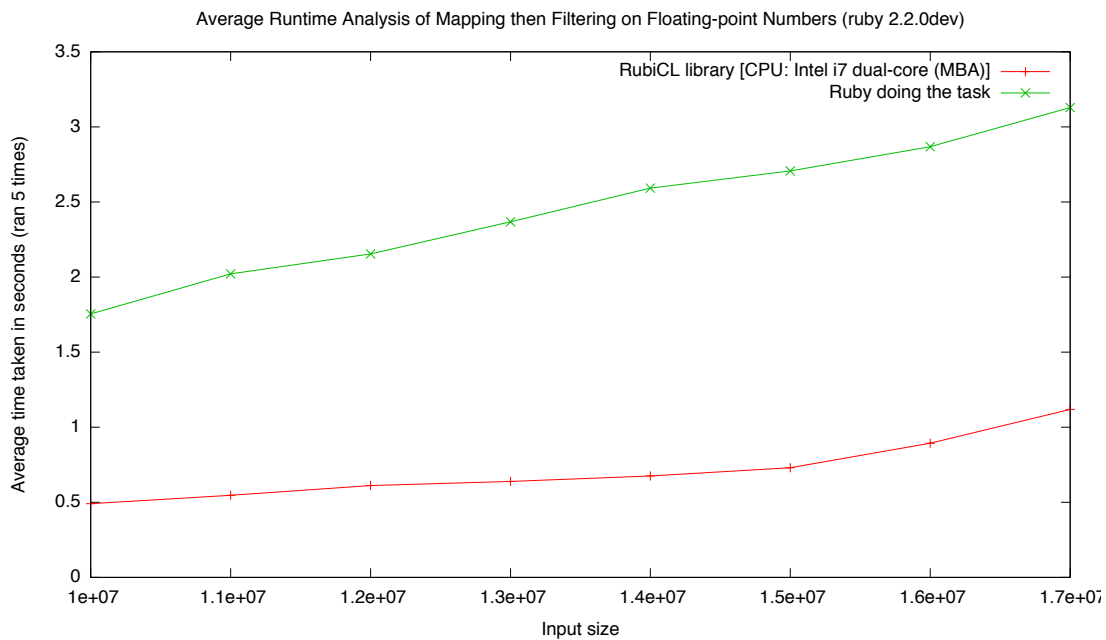


Figure 6.28: Duration for larger-scale *MapFilter* tasks on floating-point numbers

6.1.5 Sort tasks

6.1.5.1 Integer performance

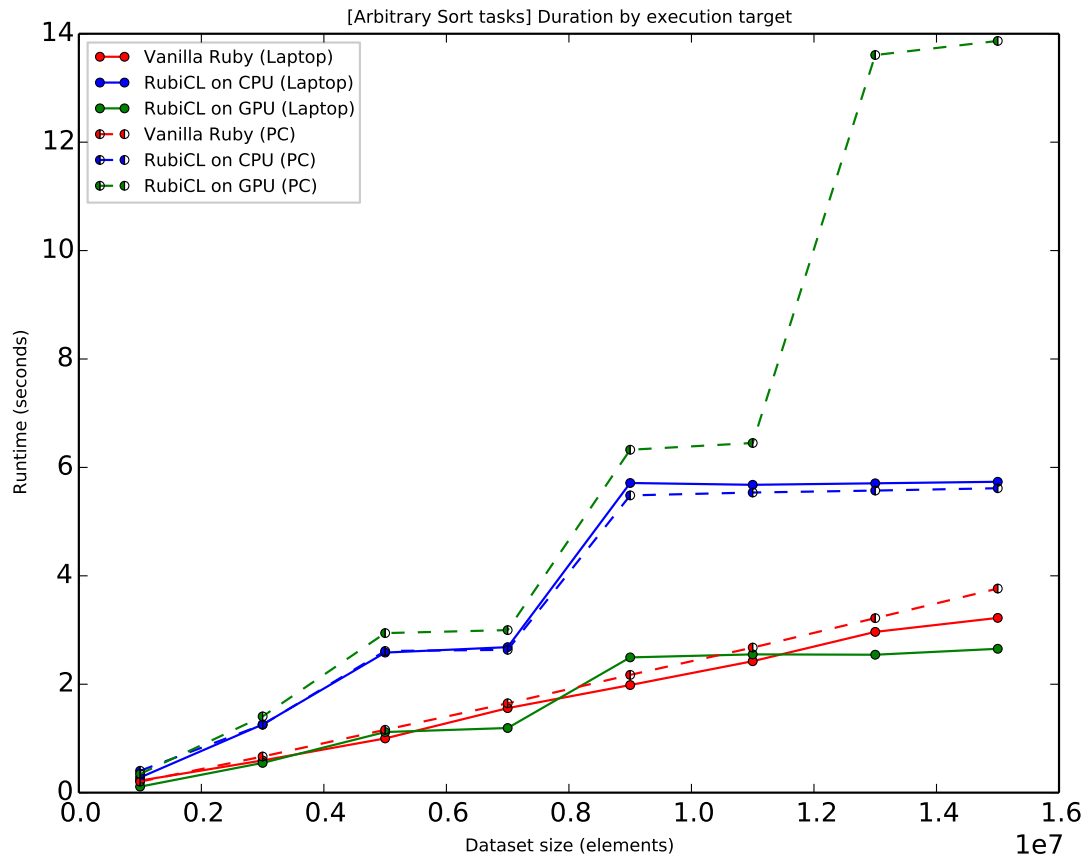


Figure 6.29: Task duration by execution target for sorting arbitrary datasets.

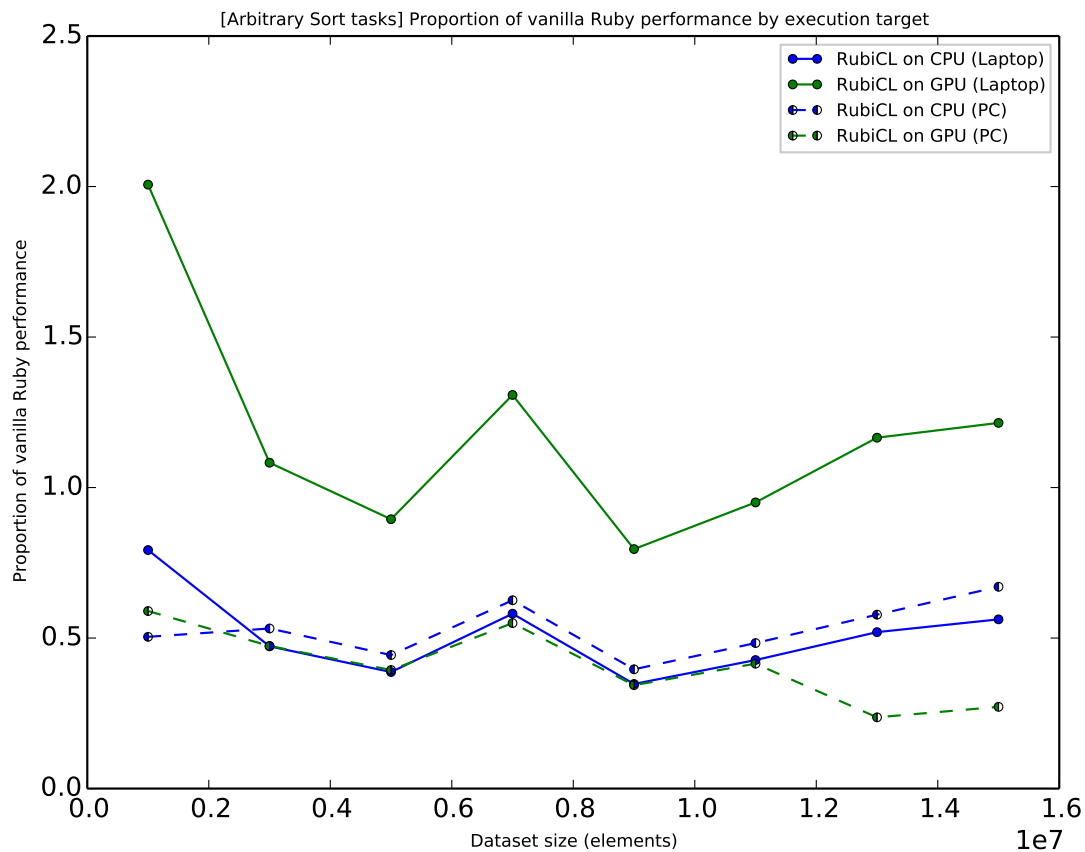


Figure 6.30: Proportion of vanilla Ruby performance achieved for sorting arbitrary datasets.

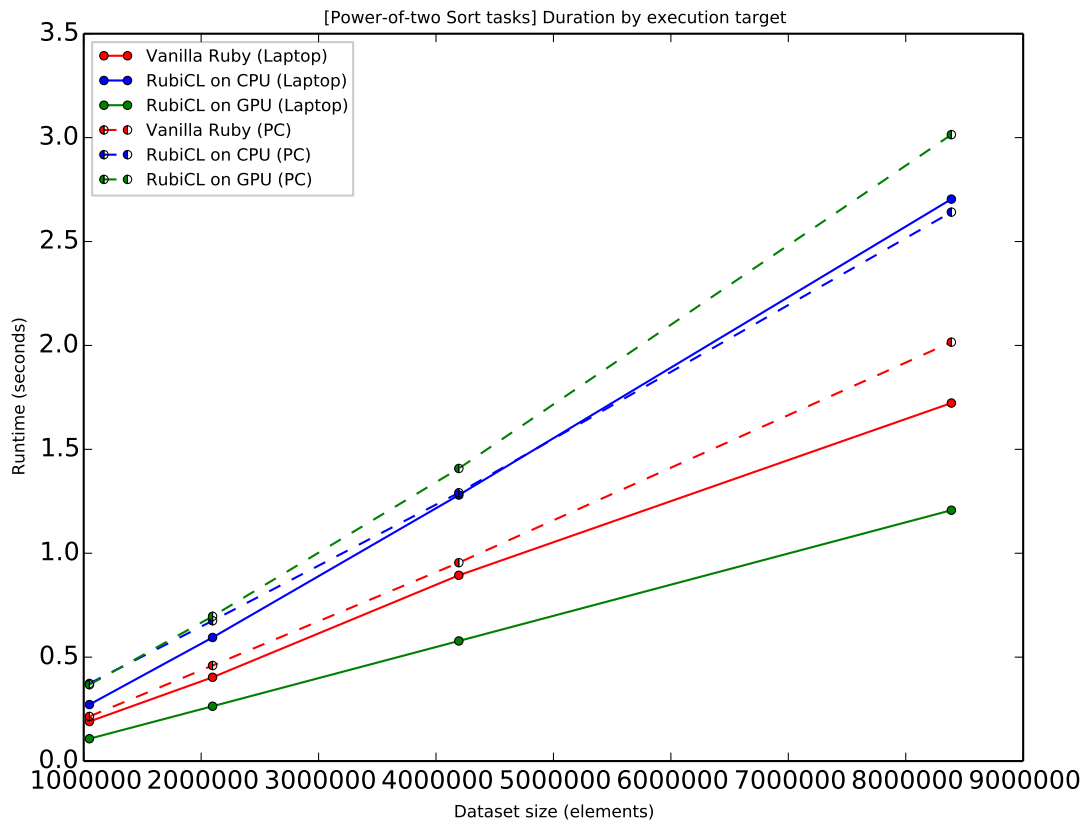


Figure 6.31: Task duration by execution target for sorting power-of-two sized datasets.

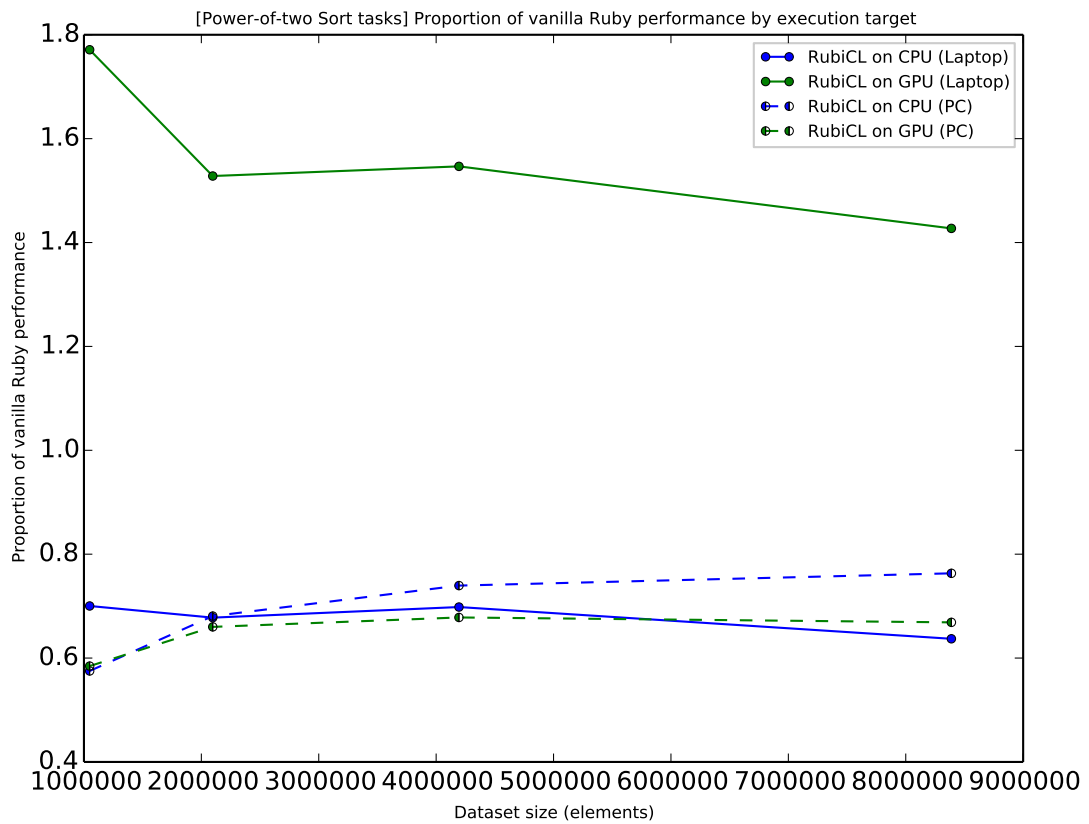


Figure 6.32: Proportion of vanilla Ruby performance achieved for sorting power-of-two sizes datasets.

6.1.5.2 Recap of operation performed

The shuffled datasets were sorted in ascending order, by triggering the sort method of the collection. RubiCL's implementation of sorting uses parallel bitonic sort. Standard Ruby 2.2 `Enumerable#sort` rely on *quicksort*.

6.1.5.3 Observations and analysis

Figure 6.29 highlights a critical flaw within RubiCL's *Sort* task implementation. Parallel bitonic sorting requires power-of-two sized datasets for the sorting network to operate correctly. In order to utilise the algorithm for general-sized sorting, the library pads the input dataset with `MAX_INT` until the next power-of-two size.

The flaw present stems from an inefficient method of padding and unpadding the dataset. First, the input dataset is copied into the trailing segment of a larger buffer that has been prepended with padding. This is far less efficient than resizing the buffer and writing padding into the end segment, although it was unclear how this could be achieved using the OpenCL API at the time that the task was implemented. Finally, the dataset is extracted from the front segment of the buffer, as it can be assumed that all padding has propagated to the end. This action uses a buffer copy again, instead of the far more efficient method of returning a sub-buffer. All this unnecessary transfer of data produces an extraneous delay governed by memory bandwidth, and drastically decreases the performance for certain ratios of padding. The inefficient code was written in an attempt to implement the feature quickly and promptly forgotten about.

A large failing of the project in this regard was the fact that benchmarking of the sorting algorithm overlooked using non-power-of-two datasets. Due to the convenience of raising 2 to a range of powers using the `map` function, this method was used to generate seed sizes within the frequently used benchmarking scripts. Figure 6.31 shows that for power-of-two datasets, sort performance is not hindered. Therefore, the inefficiency was understandably missed.

Programming error aside, the performance of the sort algorithm on the CPU of both systems is unsurprisingly lacking. The *compare-swap* bitonic sort algorithm used by RubiCL to perform sort tasks has $O(n \log^2 n)$ cost, greater than that of average-case *quicksort*. In addition, *quicksort* is particularly celebrated for minimising the number of comparisons necessary to sort a dataset, resulting in far less work than *bitonic mergesort*. The increase in throughput provided by scheduling across many hardware threads of a CPU was insufficient to offset having to perform a greater number of comparisons.

It is more interesting to note that Figure 6.32 shows when sorting an integer dataset using the laptop's GPU, performance around 1.5 times that of inbuilt *quicksort* can be achieved. It's important to realise that this does not mean GPU sorting will triumph over *quicksort* in other domains, though more efficient GPU sorting algorithms have been shown to provide significant speed-up over CPU sorting[23]. However, it is more likely in this case that a combination of no need for un-boxing variables within the RubiCL execution environment, combined with a still-strong sorting algorithm, resulted in the RubiCL implementation performing the task faster than the RubyVM could manage.

For some reason, the performance of the desktop GPU was not as strong as that of the laptop GPU. This is disappointing and further work should look into why this is the case.

6.2 User evaluation

Recap of the study performed 7 test-subjects were tasked with answering a test-file containing 5 questions. Answers to questions were obtained by querying 2 datasets of 10 million elements each, with the assistance of the project's delivered library. This section presents the raw findings of the study, alongside interpretation and analysis.

6.2.1 Results

All applicants finished the 5 question exercise within 20 minutes. In most cases, the first question took the longest amount of time to complete, with an average of 4.5 minutes. This can be explained by most people choosing to re-read the documentation and become accustomed with library usage before progressing. The next question was generally quicker to solve, with a mean of 3 minutes, as it only involved applying a filtering stage to the previous counting pipeline. The third question took longer for most applicants, at a mean of 4 minutes, as it introduced the new concepts of zipping and summation reduction. By the fourth question, subjects were more accustomed with the library's usage and it took a mean of 2 minutes to complete. The final task was quick for most applicants also, taking a mean of 2.25 minutes. In addition, most of the time was spent de-cyphering the complex requirements of the question.

6.2.2 Test demographics

The level of programming experience present in test subjects was as follows:

- 3 applicants were final-year Informatics Master's students.
- 1 applicant was a final-year Informatics Bachelor student.
- 2 applicants were third-year Informatics Bachelor students.
- 1 applicant was a graduate of an unrelated discipline, with very little prior programming experience.

Effect on performance In general, it was found that more-seasoned programmers completed the tasks sooner. Importantly though, this appeared not to be because those with less experience had difficulty. Instead, it appeared to be the case that experienced programmers could simply transcribe their thought processes into code faster, perhaps due to greater experience of thinking about execution whilst typing.

6.2.3 Observations made

- A common theme throughout all test subjects: They avoided reading documentation as much as possible until they encountered difficulties and became stuck. This highlights the need to produce a library whereby experimentation can often yield the correct answer, as

people are reluctant to have to read how something work instead of finding out for themselves.

- Forgetting to annotate a dataset with its type declaration was common for early questions. This was particularly true for subjects with prior experience of the Ruby programming language, perhaps due to the familiarity of the task causing them to write commonplace unannotated code without further thought. Luckily, this mistake became much less common after it had been made a couple of times. All subjects were less likely to make the same mistake repeatedly as they progressed through questions.
- Most people gave anonymous function parameters useless names, like *x*, when there was only one. In contrast, meaningful names, like *id*, *amount*, were used when there were several bound variables present. This justifies the project's decision to provide function parsing support, as it allows arbitrary naming of bound variables used within calculations by the programmer.
- Experienced programmers were more likely to state filtering predicates over several distinct pipeline stages, citing ease of readability as a motivating factor. This demonstrates the need to support *task-fusion* within a pipeline-based execution environment. Otherwise, there would be an unnecessary penalty associated with orchestrating queries this way.
- There was confusion as to how zipping was achieved in the library, again this was particularly prevalent among experienced Ruby programmers. This was manifested as them attempting to zip datasets after both had been annotated, despite the documentation stating that only the first dataset needs to be annotated and not the method argument. This was less common with subjects inexperienced with Ruby as they read the documentation first. This suggests that, in further work, the *zip* method should be revisited and perhaps redesigned to be more explicit in usage.
- When typos were made within parsed anonymous functions, subjects understood the error message provided. This occurred despite it mentioning "method sending not implemented for \$VARIABLE_NAME" whenever incorrectly written bound variables were interpreted as a function invocation request.
- The user with little programming experience did not find the library difficult to utilise or the questions hard to answer, after the process of stating computation as a pipeline of operators was explained. This suggests that the library may be suitable for analysts with little programming experience if they can quickly get to grips with how to orchestrate queries.
- Programmers with greater experience in the target language did a better job of highlighting inconsistent behaviour. For example, one user tried supplying a function argument to the *count* operator, something that was unimplemented at the time as it had not been considered. This inconsistency was later fixed, but its discovery demonstrated the need for expert users in addition to novices when testing usability.
- There was no correlation between prior parallel programming ability and performance in the task. When questioned about levels of previous experience after the task, several participants stated they had no idea that the library was performing queries in parallel at all.
- There was no correlation between prior GPU programming experience and task perfor-

mance. Again, when questioned, no participants were aware that execution was occurring on the laptop GPU.

6.2.4 Solution performance

Due to the questions being designed to only have one possible answering technique, all produced solutions took near-identical time to execute. Each question restarted the computation pipeline instead of carrying on, in order to keep answers distinct and easier to reason about.

The mean time of execution, on the testing laptop's GPU, for the produced solutions was 12.2 seconds. This compares favourably with the 49.5 seconds required by an identical pure-Ruby implementation, giving a speed-up factor of 4.06.

6.3 Portability

As mentioned during the *Introduction* chapter, OpenCL is still harder to utilise on some systems than the corresponding hardware vendors would have you believe.

On Apple hardware, such as the laptop used for development, achieving a working system is trivial. The system comes with all dependencies required for OpenCL GPGPU. Utilising the library is as simple as remembering to include the correct header location. For some reason Apple decided that it should live at `<openCL/opencl.h>`, while every other OS presents the OpenCL header at `<CL/cl.h>`.

On the AMD desktop system, operating *Arch Linux*, installation of a complete set of working OpenCL components was quite a bit more involved. The OpenCL framework uses a system, called Installable Client Driver (ICD), to allow many vendor-specific implementations of the library to be loaded on a single machine simultaneously.

Unfortunately, the root, vendor agnostic, ICD loader is out of date in the *Arch Linux* repositories, with only OpenCL 1.1 support. Luckily, it was possible to build `libopencl`, provided by AMD, from source and install the ICD loader correctly. Once the loader was installed, obtaining the actual ICD component was straightforward, it is contained within the AMD APP SDK, available in the Arch User Repository (AUR). However, the AMD APP SDK only provides CPU drivers for OpenCL execution. Furthermore, the default, *free* AMD display drivers do not allow OpenCL access to onboard GPU devices. The solution is to install the proprietary `catalyst-utils` package, again from the AUR. This provides required kernel modules for AMD GPU utilisation.

The final remaining issue is that `catalyst-utils` only supports a significantly out of date version of `xorg-server`. This could cause issues in a system used for daily activities, as dependency clashes could leave the user having to choose between OpenCL support and the ability to run recently-developed desktop software.

Chapter 7

Conclusions

7.1 Success of the project at achieving its aims

7.1.1 Improving the performance of dynamic languages when executing data driven tasks

The distinct task benchmarks, shown in the *Results* chapter, demonstrate that the development system achieved a speed-up of 3.5–9 times for all parallelised higher-order functions, given enough input data to offset task latency. Greater improvement over standard Ruby can be obtained when users have split a complex stage of a pipeline into multiple smaller stages, for conceptual simplicity, as this does not negatively affect the project’s execution performance.

In addition to excelling in artificial benchmarks, the library performed well in the realistic scenario presented during user testing, with a measured speed-up factor of 4.06.

Importantly, increased execution throughput occurred at often-achieved dataset sizes. While the highest rates of speedup required over a million items, the RubiCL library started responding to tasks faster than the default implementation at just 20,000–25,000 elements for *Map* and *Map-Filter* tasks, and 50,000 elements when solely filtering.

However, deciding how much credit to give to parallelism for these results is another matter. Custom native-extension code was benchmarked and outperformed the library in all task types apart from pure-*Map*. Furthermore, this ‘optimal’ solution only utilised a single thread of execution. Therefore, it is clear that utilisation of highly-parallel devices did not boost performance past sequentially obtainable levels.

This result of parallelism being ineffective is not conclusive though, as knowing that you have produced an optimal parallel solution is much harder than with sequential code. It is likely that several performance breakthroughs are possible within the library’s implementation, especially since high performance OpenCL programming is still regarded as somewhat of a *black art*.

It is likely that a high proportion of the speed-up, achieved by both the native extension and the project’s solution, is due to aversion of the need to un-box variables individually and then retrieve the behaviour for the operators requested, given the resultant type.

As a means to generate code that sidesteps method-cache lookup, OpenCL works well. Its notion of *kernel* dispatch is a useful metaphor when batching requested operations for execution and then retrieving results. Its inclusion into the project simplified the challenge of translating high-level function objects into low-level execution instructions, something that would be unclear how to achieve otherwise. Finally, the library provides the ability to execute on arbitrary parallel compute-devices. It is possible that in future, with increases in either OpenCL performance or *processing-unit* density, a higher ratio of bespoke code performance will be obtained.

7.1.2 Facilitating a larger scale of experimentation in a REPL environment by non-expert users

User evaluation performed suggested that the complexity of the produced system was not too great for utilisation by non-experts. The library was designed to allow complete agnosticism of parallel programming techniques and paradigms for execution on non-CPU devices. As a result, it should be accessible to anyone who understands how to manipulate the results of a pipeline computation, and how higher-order functions can be used to transform datasets.

However, the sample size for usability testing was far too small and further research is necessary to verify ease-of-use claims with any confidence.

MapFilter tasks, commonly used in REPL environments when answering queries, experienced at best a 9 times speed-up through utilisation of the project's deliverable. This result is significant when considering the usage patterns of interactive programming. With the RubiCL library, an involved query taking 10 seconds to complete will require minimal user patience before results are returned to be interpreted. The same query could take 1.5 minutes to complete without redirecting computation to a more efficient implementation. With this level of delay, the end-user is far more likely to become impatient and get distracted, taking a coffee break or experiencing another pitfall resultant in a costly mental context-switch.

7.1.3 Exploring the extensibility of the Ruby programming language

When designing the interface for the library, several constraints were placed on syntax in order to achieve desired functionality. Firstly, it was necessary to add annotation to the start and end of the computation pipeline. Without annotation, it would be impossible for the standard RubyVM implementation to judge whether all elements within a collection object were of a uniform type, save the costly task of examining them in sequence. Secondly, without providing delimiters for the start and end of computation it would be impossible to defer tasks and dispatch fewer combined tasks later. This is because each method within a pipeline is transformed into an invocation stack-machine instruction as soon as the token corresponding to its name has terminated, either from a subsequent call or a newline token.

Given these requirements, the interface presented for specifying computation is opaque as possible. Programmers using the library have no knowledge of how work is segmented for parallel processing. The target compute-device utilised is unknown unless it has been explicitly set. The project succeeds at only inconveniencing users with providing the bare minimum of information required for its operation, and no more.

As the library’s functionality is itself provided by a native extension, this project shows that expanding the capabilities of the Ruby language in this manner is a simple and effective way of speeding-up performance critical tasks. This ease of extension can be embraced by the design paradigm of first building something that works and then continually improving it. Sections of code that are producing the majority of run-time can be replaced with custom native extension or other methods of offloading tasks.

The RubiCL library allows programmers to effortlessly offload computationally intensive tasks to a more efficient implementation from the start. This reduces the need to worry about revisiting these sections later, as long as the required minimum dataset sizes for speedup are reached.

7.1.4 Effective code generation and reuse on the OpenCL platform

When producing the kernel generation subsystem, it was found that the simplicity of OpenCL syntax, much like C syntax, facilitated this task. The operation of translating parsed instruction tokens into an equivalent kernel was straightforward enough. However, this stage would be far more elegant if LLVM IR could be output by the parser instead, and mapped to a compiled OpenCL kernel object. This would avoid the fragility of string handling during code generation altogether. Furthermore, it would replace the program compilation stages of the project’s back-end library, leaving it conceptually leaner, as compiled kernel object code can be fetched and executed instead. Capability to achieve this is currently lacking, with several projects attempting to provide LLVM-to-OpenCL mapping but none yet at a useful stage of development. A breakthrough here would make arbitrary task generation on parallel devices much easier.

Within the project’s development cycle, it was found that reuse of certain parallel primitives was possible, this greatly reduced the duplication of coding effort. Examples of how this composition was achieved can be observed in this report’s *Implementation* chapter. Successful utilisation of previously defined primitives over multiple tasks was aided by the library’s back-end design. At one level of abstraction, all required transformations of a dataset given a task object were defined. The native extension, used to provide method functionality to the library’s Ruby run-time, merely triggered combinations of these primitives in order to perform each type of parallel task. How well this style of reuse can be achieved in other projects will vary greatly with how general the required operations over datasets are.

7.1.5 Applicability to a variety of platforms, avoiding over-tailoring for a specific machine

The desktop system successfully experienced task speed-up after utilising the project library to perform tasks. However, it did not perform as well as was expected after witnessing the initial success of the development system. Specifically, 2–4 times speed-up of tasks was achieved, but this pales in comparison to the factors of 3.5–9 displayed during laptop benchmarking.

More significantly, the number of dataset elements required for beneficial outsourcing of computation rose from tens of thousands to 2 million–5 million. It is likely that the greater task dispatch latency experienced on the desktop system, 300ms as opposed to 50ms, is to blame for this elevated lower-bound. Unfortunately, it is less clear what the cause for this increased delay is. It was

expected that GPU tasks would experience higher latency, due to the need to transfer datasets over the PCI bus. Yet, a comparable delay was experienced by the CPU device as well. After the issues faced correctly installing AMD OpenCL support on *GNU/Linux*, it is possible that suboptimal driver performance may have some part to play. Nonetheless, this issue should be investigated further in order to increase the applicability of the project's deliverable on desktops.

The rate of GPU acceleration did seem like it could reach over 4 times that of the standard implementation when filtering the larger datasets, as it showed no sign of plateauing on the performance graphs. Without further benchmarking it will be impossible to know whether this is the case.

Another oddity experienced on the desktop system was the fact that sort task performance was lower on the GPU than the CPU. This is unexpected as the algorithm used was designed for massively parallel architectures at the expense of extra work. This hints that the hardware wasn't being utilised fully, but again only further research can determine what went wrong.

Finally, it must be reiterated that it is currently quite involved to setup a working *GNU/Linux* AMD OpenCL compute system. The need for proprietary drivers that do not play nicely with the default graphics tool-chain to be installed before tasks can be accelerated reduces the number of eligible systems significantly.

With all the issues encountered, this goal experienced only partial success. Sizeable performance improvements were still provided for desktop system computation. However, they required a much larger dataset to offset the sizeable latency, and the system setup phase was harder than anticipated. Hopefully, installation issues will decrease over time as uptake increases.

7.2 Further work

This section contains a mixture of work that was initially planned but left uncompleted due to time constraints, and bolder ideas for improvement that could be of interest if project development was revisited.

Greater optimisation of generated kernel code Introducing greater complexity to the OpenCL kernel source returned by the code generation subsystem has the potential to provide further speed-up. Namely, it does not currently utilise vector instructions when performing arithmetic operations. Instead of loading a single element at a time and performing n distinct additions when incrementing a dataset, k elements can be retrieved at once from the buffer in each kernel invocation and processed using k -width vector addition. This way, only $\frac{n}{k}$ distinct operations are scheduled on the compute-unit. Implementing this feature would also involve reducing the number of work units scheduled by a factor of k . This was initially a goal during project development but was abandoned in favour of creating a working system first and revisiting it to optimise later. Unfortunately, since time ran out, this previous goal was never revisited.

Arbitrary length tuples Again, as a result of striving for simplicity during the project's development phase, tuple support was only added when dealing with tuples of length 2. Instead of duplicating primitive calling code with the ability to provide an additional buffer as a kernel argument, back-end code should be genericised to allow a buffer collection to be passed to any invoked

kernel. Such an implementation would allow the loading of any number of distinct slot buffers, with the kernel still providing ‘virtual’ tuple behaviour. This is more involved than the current solution, but would allow general tuple behaviour without the need to keep introducing duplicated code supporting additional tuple slots.

Greater number of tuple-compatible primitives Currently the system only supports creation, mapping, filtering, and combining of tuple elements. This should be expanded to support sorting of tuples. Sorting in general should be improved to accept function arguments to sort the input elements by. After the system is expanded to permit sorting of tuples, the group-by primitive could be implemented without great difficulty. Finally, by introducing arbitrary reduction of tuple sets, functionality of frameworks, such as *MapReduce*, geared for processing of *key, value* pairs could be provided on top of the RubiCL library.

Investigation of latency issues on tested desktop system As mentioned earlier, it is unknown why the desktop system’s experienced latency was significantly higher than that of the development laptop. It is worthwhile investigating if there is a simple fix to this strange behaviour, by spending more time studying the behaviour of the library. Latency is an important issue to overcome when producing an acceleration library designed for general use, as it rules out operation on smaller datasets that occur more commonly.

Integration with the Topaz VM *Topaz*[24] is an alternate implementation of the Ruby programming language, written using the RPython VM tool-chain. This makes it similar to the *PyPy* project, responsible for a fast alternate version of the *Python* language benefiting from many optimisations including Just-In-Time (JIT) compilation.

One issue experienced by the project, due to relying on the standard RubyVM, was the fact that processed array elements are initially stored in non-continuous memory. This meant that when loading integers from a dataset created in Ruby, the project’s native extension had to loop over each index and request the element with that index within the array from the VM. A relevant optimisation present in Topaz is that it keeps track of the type of elements inserted into a collection. When all elements are of a single basic type, the raw values are stored, un-boxed, in continuous memory. This storage mechanism would render the process of retrieving each variable from its memory location unnecessary. Furthermore, it would be possible to pin the array, used by the Topaz VM to store the raw values, directly into device memory and then perform *Map* or *Filter* tasks upon it. This would greatly reduce the amount of data copied and therefore positively affect latency.

In addition, since the Topaz VM keeps track of the basic type of values within an un-boxed array, RubiCL type annotations would no longer be required. Since pipeline delimitation is still necessary, it could be reduced to calling methods with names such as *#defer* and *#to_a* (cast to Array).

Concurrent cooperative processing on compute-devices This was initially attempted during the final phase of the project’s development, but abandoned due to the original design introducing too much overhead. It should be possible to perform a task pipeline by scheduling computation transforming dataset subsets on both compute-devices concurrently. For example the speed-up factors of GPU/CPU *MapFilter* tasks on the development laptop are roughly 8/6 at both 10 million

7.2. Further work

and 20 million elements. Therefore, when a *MapFilter* pipeline is performed, it should be possible to place $\frac{8}{14} \times 20,000,000 \approx 11,500,000$ elements on the GPU and $\frac{6}{14} \times 20,000,000 \approx 8,500,000$ elements on the CPU and have the two devices finish processing tasks at roughly the same time. Moreover, processing 20,000,00 elements should now only take as long as it would take for the laptop to process 11,500,000 elements originally. The disjoint buffers can then be combined when a result is requested, using the appropriate combination operator. For example, addition would be an appropriate combination if the sum of both sub-buffers had been calculated. Difficulty stems from the need to know what ratios will produce sub-problems that finish at the same time, requiring further analysis of the parallel computation cost model. In addition, necessary movement of data can introduce significant performance penalties, such as exchanging elements between separately sorted sub-buffers prior to a scan occurring. However, these pathological cases could be detected during *TaskQueue* optimisation and hybrid execution avoided in these circumstances.

RubyGem deployment system Currently, utilising the project's deliverable requires cloning the *Git* repository, generating a *Makefile*, and running the make tool, before the library can be included into a Ruby run-time. *RubyGems*[25] is a hosting service for packaged libraries written for the Ruby language. The library container, referred to as a *Gem*, handles building any native extensions that may be required. By packaging the RubiCL library as a Gem and then hosting it on RubyGems, installation would be as simple as `$ gem install rubi_cl`. The library is then available to be required by suitable code on the system. Making it trivial to install and subsequently outsource computation with the RubiCL library is important if many others can benefit from the project's increased calculation throughput.

Bibliography

- [1] Gordon E Moore et al. Cramming more components onto integrated circuits, 1965.
- [2] Herb Sutter. The free lunch is over: A fundamental turn toward concurrency in software. *Dr. Dobbs's Journal*, 30(3):202–210, 2005.
- [3] Deborah T Marr, Frank Binns, David L Hill, Glenn Hinton, David A Koufaty, J Alan Miller, and Michael Upton. Hyper-threading technology architecture and microarchitecture. *Intel Technology Journal*, 6(1), 2002.
- [4] Georgios Tournavitis, Zheng Wang, Björn Franke, and Michael FP O’Boyle. Towards a holistic approach to auto-parallelization: integrating profile-driven parallelism detection and machine-learning based mapping. In *ACM Sigplan Notices*, volume 44, pages 177–187. ACM, 2009.
- [5] Bingsheng He, Wenbin Fang, Qiong Luo, Naga K Govindaraju, and Tuyong Wang. Mars: a mapreduce framework on graphics processors. In *Proceedings of the 17th international conference on Parallel architectures and compilation techniques*, pages 260–269. ACM, 2008.
- [6] Jeffrey Dean and Sanjay Ghemawat. Mapreduce: simplified data processing on large clusters. *Communications of the ACM*, 51(1):107–113, 2008.
- [7] Max Grossman, Mauricio Breternitz, and Vivek Sarkar. Hadoopcl: Mapreduce on distributed heterogeneous platforms through seamless integration of hadoop and opencl. In *Proceedings of the 2013 IEEE 27th International Symposium on Parallel and Distributed Processing Workshops and PhD Forum*, pages 1918–1927. IEEE Computer Society, 2013.
- [8] Konstantin Shvachko, Hairong Kuang, Sanjay Radia, and Robert Chansler. The hadoop distributed file system. In *Mass Storage Systems and Technologies (MSST), 2010 IEEE 26th Symposium on*, pages 1–10. IEEE, 2010.
- [9] aparapi: Api for data parallel java. <https://code.google.com/p/aparapi/>.
- [10] Cudafy.net. <https://cudafy.codeplex.com/>.
- [11] Manuel MT Chakravarty, Gabriele Keller, Sean Lee, Trevor L McDonell, and Vinod Grover. Accelerating haskell array codes with multicore gpus. In *Proceedings of the sixth workshop on Declarative aspects of multicore programming*, pages 3–14. ACM, 2011.
- [12] Hackage: Data.array.accelerate. <http://hackage.haskell.org/package/accelerate>.
- [13] Trevor L McDonell, Manuel MT Chakravarty, Gabriele Keller, and Ben Lippmeier. Optimising purely functional gpu programs. In *Proceedings of the 18th ACM SIGPLAN international conference on Functional programming*, pages 49–60. ACM, 2013.

- [14] Rake, ruby make. <http://rake.rubyforge.org/>.
- [15] Sinatra. <http://www.sinatrarb.com/>.
- [16] Wikipedia: Duck test. http://en.wikipedia.org/wiki/Duck_test.
- [17] Khronos group: The open standard for parallel programming of heterogeneous systems. <https://www.khronos.org/opencv/>.
- [18] The ruby programming language. <https://www.ruby-lang.org/en/>.
- [19] Justin Talbot, Richard M Yoo, and Christos Kozyrakis. Phoenix++: modular mapreduce for shared-memory systems. In *Proceedings of the second international workshop on MapReduce and its applications*, pages 9–16. ACM, 2011.
- [20] Marwa Elteir, Heshan Lin, Wu-chun Feng, and Tom Scogland. Streammr: an optimized mapreduce framework for amd gpus. In *Parallel and Distributed Systems (ICPADS), 2011 IEEE 17th International Conference on*, pages 364–371. IEEE, 2011.
- [21] Rspec, a testing tool for the ruby programming language. <http://rspec.info/>.
- [22] User evaluation hints, a github gist. <https://gist.github.com/cronin101/9772637>.
- [23] Erik Sintorn and Ulf Assarsson. Fast parallel gpu-sorting using a hybrid algorithm. *Journal of Parallel and Distributed Computing*, 68(10):1381–1388, 2008.
- [24] Topaz. <https://github.com/topazproject/topaz>.
- [25] Rubygems. <http://rubygems.org/>.