

University of Cyprus
Department of Computer Science

Exploring Swift as a Serverless Language on OpenWhisk

Andreas Loizides

Mentor: Dr Haris Volos

May 2023

Acknowledgements

I would like to express my profound gratitude to a number of people whose support and contributions were invaluable throughout the course of this thesis.

First and foremost, I would like to thank my mentor, Dr. Haris Volos, for his unwavering guidance and continuous support. Whenever issues arose, Dr. Volos was always ready to thoroughly evaluate the problem, imparting not only his expert knowledge but also a sense of shared purpose and curiosity. His dedication to my research gave me the confidence and motivation to navigate the complex challenges that arose during this thesis. It truly felt like we shared the same research goals and the drive to satisfy curiosity which is crucial in a research context. His care and attention were instrumental in enabling me to reach my research goals.

I am deeply grateful to my university for granting me access to the CloudLab's infrastructure. This access was not just a privilege but a necessity. The comprehensive results and the eventual completion of this thesis would not have been possible without it. It provided a robust platform to explore Swift as a serverless language on OpenWhisk, contributing significantly to the outcomes of my research.

Lastly, but by no means least, I would like to extend my heartfelt thanks to my parents. Their unconditional faith in my abilities and their financial support provided a stable foundation for my academic journey. It allowed me to comfortably pursue my interests and devote my energy to my research. Their sacrifices and belief in my vision were a beacon of light that guided me through the most challenging phases of this thesis.

To all of you, thank you. This accomplishment would not have been possible without your collective support and belief.

Abstract

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetur id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

Contents

Acknowledgements	i
Abstract	iii
1 Introduction	3
1.1 Background	3
1.2 Research Questions	3
2 Performance Comparison	5
2.1 Value Types vs Reference Types and Copy-On-Write	5
2.2 Qualitive Comparison with Go, Java, Javascript, and Python	6
2.3 Summary	11
3 Cold Start Analysis of Serverless Languages on OpenWhisk	13
3.1 Introduction	13
3.2 Background and Related Work	13
3.3 Benchmark Functions Selection	13
3.4 OpenWhisk Setup and Configuration	13
3.5 Methodology	13
3.6 Results and Analysis	13
3.7 Factors Affecting Cold Start Times	13
3.8 Discussion and Interpretation	13
3.9 Conclusion	13
4 Ease of Development	15
4.1 Language Simplicity and Syntax	15
4.2 Available Libraries and Frameworks	22
5 Synchronization System Case Study	29
5.1 System Overview	29
5.2 Experimental Setup	29
5.3 Benchmarking Process	29

5.4	Results and Discussion	34
5.5	Improvements and Future Work	35
5.6	Conclusion	35

Chapter 1. Introduction

1.1. Background

1.2. Research Questions

1.2.1 Performance Comparison

How does the performance of Swift compare to other serverless languages, such as Python, Java, and Node.js? We can run synthetic benchmarking workloads on OpenWhisk to compare the performance of Swift with other languages.

1.2.2 Cold Start Analysis

Cold start refers to the time taken to initialize a new serverless function. How does the cold start time of Swift compare with other serverless languages? We can use OpenWhisk to run tests to analyze the cold start time of Swift.

1.2.3 Ease of Development

How easy is it to develop serverless functions in Swift compared to other languages? We can evaluate the development experience of Swift by comparing it with other serverless languages.

1.2.4 Resource Utilization

How efficiently does Swift utilize serverless resources, such as CPU and memory? You can use OpenWhisk to monitor resource utilization and analyze the efficiency of Swift in utilizing these resources.

1.2.5 Cost Analysis

How does the cost of running serverless functions in Swift compare with other languages? We can compare the cost of running Swift functions on OpenWhisk with the cost of running functions in other serverless languages.

Chapter 2. Performance Comparison

2.1. Value Types vs Reference Types and Copy-On-Write

In programming languages, value types and reference types represent two ways to handle data. Understanding the difference between them and their performance implications is crucial to making informed decisions when choosing a language for serverless applications. Swift not only distinguishes between value and reference types, but also employs Copy-On-Write optimization for most of its value types, including collections such as Arrays, Dictionaries, and Sets.

2.1.1 Value Types

Value types are types for which the value is stored directly in the memory. When a value type is assigned or passed to a function, a separate copy of the value is created. The main benefit of value types is that they are generally more efficient in terms of memory usage and can result in more predictable performance. In Swift, the distinction between value and reference types is handled through structs (value types) and classes (reference types).

2.1.2 Reference Types

Reference types represent data where the memory location (or reference) is stored, rather than the data itself. When a reference type is assigned or passed to a function, the reference (memory address) is copied, not the actual data. This means that different variables can point to the same data, potentially leading to unexpected behavior if the data is modified.

2.1.3 Copy-On-Write (CoW)

Swift uses Copy-On-Write (CoW) for most of its value types, including collections such as Arrays, Dictionaries, and Sets. Collections whose Element type is also a value type essentially leverage CoW for free. CoW is an optimization strategy

where the copying of a value type is delayed until it's necessary, i.e., when the value needs to be modified.

This approach has several performance benefits when compared to simply copying the data every time:

- Sharing the same data among multiple instances of a collection is more memory efficient, as multiple copies of the same data are not required.
- When a value is not modified, the overhead of data copying is eliminated, resulting in improved performance.
- Copying is performed only when modifications are made, avoiding unnecessary data duplication.

2.1.4 Performance Benefits

The distinction between value and reference types, as well as Swift's usage of CoW, has several implications for performance:

- Value types with CoW can lead to more predictable performance, as the compiler can make better optimization decisions when it knows that data cannot be shared or modified externally. Furthermore, the actual data copying is delayed until it's necessary.
- Copying value types can be faster, as the memory layout is more predictable and can often be associated with better cache utilization.
- Avoiding the overhead of managing memory references for reference types can result in performance improvements, as fewer indirections are needed for memory access.

In summary, the distinction between value and reference types in a language like Swift, combined with the use of Copy-On-Write optimizations, provides developers with fine-grained control over memory handling and potentially leads to better performance when compared to languages that do not offer such a distinction. These aspects make Swift an attractive choice for serverless applications where performance is critical.

2.2. Qualitative Comparison with Go, Java, Javascript, and Python

Is the distinction between value types and reference types achievable in each language? Is any benefit from the distinction possible in each language? In this section,

we will compare the distinction between reference and value types in Swift to Go, Python, Node.js (JavaScript), and Java. We will examine whether these languages offer a similar distinction, and if any benefits from the distinction are achievable in each language.

2.2.1 Go

Go supports both reference types and value types. In Go, structs are used as value types, while slices, maps, and channels are some examples of reference types.

Value types in Go: When a value type variable is assigned or passed to a function, a copy of the value is created. Consider the following example:

```
package main

import "fmt"

type Point struct {
    X int
    Y int
}

func main() {
    p1 := Point{1, 2}
    p2 := p1
    p2.X = 3

    fmt.Println(p1) // Output: {1 2}
    fmt.Println(p2) // Output: {3 2}
}
```

In this example, assigning `p1` to `p2` creates a separate copy of the value, hence changing `p2.X` does not affect `p1`.

Reference types in Go: While Go also has reference types, like slices, they behave differently than reference types in Swift. Here's an example using slices:

```
package main

import "fmt"
```

```

func main() {
    s1 := []int{1, 2, 3}
    s2 := s1
    s2[0] = 9

    fmt.Println(s1) // Output: [9 2 3]
    fmt.Println(s2) // Output: [9 2 3]
}

```

In this case, assigning `s1` to `s2` creates a reference to the same slice. Modifying `s2[0]` affects `s1` as well.

Although Go has value and reference types, it does not support Copy-On-Write (CoW) optimizations like Swift, limiting its potential for similar performance improvements.

2.2.2 Python

Python, being a dynamically typed language, does not explicitly provide separate value and reference types. However, the distinction can still be made between mutable and immutable objects, which relates to the concept of value and reference types.

Immutable objects: Immutable objects like tuples, strings, and frozensets behave similarly to value types:

```

t1 = (1, 2)
t2 = t1
t2 += (3,)

print(t1) # Output: (1, 2)
print(t2) # Output: (1, 2, 3)

```

In this example, updating `t2` by adding a new element does not affect `t1`.

Mutable objects: Mutable objects like lists, dictionaries, and sets behave more like reference types:

```

l1 = [1, 2, 3]
l2 = l1

```

```
12[0] = 9
```

```
print(l1)  # Output: [9, 2, 3]
print(l2)  # Output: [9, 2, 3]
```

Here, assigning `l1` to `l2` creates a reference to the same list. Modifying `l2[0]` affects `l1` as well.

Python's performance characteristics are quite different from languages like Swift and Go. As Python does not have a built-in CoW mechanism and is generally slower due to its dynamic typing and interpreted nature, the benefits achievable from the distinction between value and reference types are comparatively limited.

2.2.3 Node.js (JavaScript)

JavaScript, the language used in Node.js, is also dynamically typed and principally uses reference types. All objects in JavaScript are reference types, including arrays and functions.

Reference types in JavaScript: When an object is assigned or passed to a function, it's the reference that is passed, not the actual data:

```
let arr1 = [1, 2, 3];
let arr2 = arr1;
arr2[0] = 9;

console.log(arr1); // Output: [ 9, 2, 3 ]
console.log(arr2); // Output: [ 9, 2, 3 ]
```

In this example, assigning `arr1` to `arr2` creates a reference to the same array. Modifying `arr2[0]` affects `arr1` as well.

Simulating value types in JavaScript: Although JavaScript does not have native value types, developers can simulate value-like behavior using techniques such as object cloning:

```
function clone(obj) {
    return JSON.parse(JSON.stringify(obj));
}

let obj1 = { x: 1, y: 2 };
```

```
let obj2 = clone(obj1);
obj2.x = 3;

console.log(obj1); // Output: { x: 1, y: 2 }
console.log(obj2); // Output: { x: 3, y: 2 }
```

Despite being able to simulate value types, the distinction between value and reference types in JavaScript is not as natural as it is in Swift. Furthermore, JavaScript lacks built-in CoW optimizations, limiting the performance benefits that can be derived from the distinction.

2.2.4 Java

Java, being an object-oriented language, primarily deals with reference types like classes and interfaces. Primitive types in Java, like `int`, `float`, and `boolean`, are value types.

Value types in Java: Java's primitive types are value types:

```
int a = 1;
int b = a;
b = 3;

System.out.println(a); // Output: 1
System.out.println(b); // Output: 3
```

In this case, assigning `a` to `b` creates a separate copy of the value. Changing the value of `b` does not affect `a`.

Reference types in Java: Java's objects behave as reference types:

```
List<Integer> list1 = new ArrayList<>(Arrays.asList(1, 2, 3));
List<Integer> list2 = list1;
list2.set(0, 9);

System.out.println(list1); // Output: [9, 2, 3]
System.out.println(list2); // Output: [9, 2, 3]
```

In this example, assigning `list1` to `list2` creates a reference to the same list. Modifying an element in `list2` affects `list1` as well.

Java has a more explicit distinction between value (primitive types) and reference types (objects). However, since Java does not have CoW optimizations like Swift, the potential performance benefits from such distinctions are more limited in comparison.

2.3. Summary

In summary, all five languages – Swift, Go, Python, JavaScript (Node.js), and Java – offer some degrees of distinction between value and reference types or related concepts (mutable/immutable objects). The distinction is often more explicit in statically-typed languages like Swift, Go, and Java, while dynamically-typed languages like Python and JavaScript handle the distinction via mutable/immutable objects or using programmer-provided methods for simulating value types.

However, the primary differentiator for Swift is its built-in Copy-On-Write (CoW) optimization for value types. This feature allows Swift to offer performance benefits for serverless applications that may not be as easily achievable in other languages under comparison. Performance improvements, both in terms of memory usage and execution time, can be derived from the proper understanding and application of the distinction between value and reference types, as well as making the most of the CoW optimization in Swift.

Chapter 3. Cold Start Analysis of Serverless Languages on OpenWhisk

3.1. Introduction

3.2. Background and Related Work

3.3. Benchmark Functions Selection

3.4. OpenWhisk Setup and Configuration

3.5. Methodology

3.5.1 Deployment and Timing Approach

3.5.2 Fairness and Consistency

3.6. Results and Analysis

3.6.1 Quantitative Results

3.6.2 Comparative Analysis

3.7. Factors Affecting Cold Start Times

3.8. Discussion and Interpretation

3.9. Conclusion

Chapter 4. Ease of Development

How easy is it to develop serverless functions in Swift compared to other languages? We can evaluate the development experience of Swift by comparing it with other serverless languages.

4.1. Language Simplicity and Syntax

Swift is a modern, expressive, and safe programming language designed for performance and ease of use. Its simplicity and syntax make it a strong candidate for serverless functions. In this section, we will examine how Swift's syntax compares to other languages and how it contributes to a better development experience.

Simplicity in Swift

Swift's syntax aims to be concise and clear, which can lead to shorter and more readable code. For instance, consider the following example of declaring a constant in Swift:

```
let numberOfDays = 7
```

This is similar to Python:

```
number_of_days = 7
```

However, in Java, the declaration is more verbose:

```
final int numberOfDays = 7;
```

Swift's simplicity becomes more evident when dealing with more complex constructs, such as optional values. In Swift, optional values are handled using the `'?` and `!` operators, making it easy to declare and unwrap optional values:

```
let optionalValue: Int? = 42
let unwrappedValue: Int = optionalValue!
```

In comparison, Java uses ‘Optional’ containers, which leads to more verbose code:

```
Optional<Integer> optionalValue = Optional.of(42);  
int unwrappedValue = optionalValue.get();
```

Safety Features

Swift’s syntax includes features that promote safe programming practices and reduce the likelihood of errors. One such feature is the guard clause. The guard statement allows developers to perform early exits from a function or loop, simplifying the code and making it more readable. With the compiler enforcing early exits, developers are less likely to introduce errors.

Here’s an example of a guard clause in Swift:

```
func processInput(_ input: String?) {  
    guard let unwrappedInput = input else {  
        print("Invalid input")  
        return  
    }  
  
    // Continue processing with unwrappedInput  
}
```

A similar function in Python might use a conditional statement:

```
def process_input(input: Optional[str]):  
    if input is None:  
        print("Invalid input")  
        return  
  
    # Continue processing with input
```

While both versions are readable, the Swift version explicitly enforces the early exit, making it less prone to errors.

Readability

Swift’s syntax and features contribute to more readable code. For example, Swift’s type inference system allows developers to write cleaner code without explicitly declaring types:

```
let message = "Hello, world!"
```

In contrast, Java requires explicit type declarations:

```
String message = "Hello, world!";
```

Additionally, Swift's support for functional programming constructs, such as map, filter, and reduce, can make code more readable and expressive. Here's an example of filtering and transforming an array in Swift:

```
let numbers = [1, 2, 3, 4, 5]
let evenSquares = numbers.filter { $0 % 2 == 0 }.map { $0 * $0 }
```

A similar operation in Java is more verbose and less expressive:

```
List<Integer> numbers = Arrays.asList(1, 2, 3, 4, 5);
List<Integer> evenSquares = numbers.stream()
    .filter(n -> n % 2 == 0)
    .map(n -> n * n)
    .collect(Collectors.toList());
```

Copy-on-Write (CoW)

Copy-on-write (CoW) is an optimization technique that Swift uses to minimize memory usage and improve performance when working with value types like arrays, dictionaries, and strings. CoW delays the copying of a value until it is modified, reducing unnecessary copying and memory overhead.

Here's an example of CoW in action:

```
var array1 = [1, 2, 3]
var array2 = array1
array2.append(4)
```

In this example, 'array1' and 'array2' initially share the same underlying storage. When 'array2.append(4)' is called, Swift detects that the storage is shared and creates a separate copy of the storage for 'array2' before appending the value.

A similar example in Java does not benefit from the CoW optimization:

```
List<Integer> list1 = new ArrayList<>(Arrays.asList(1, 2, 3));
List<Integer> list2 = new ArrayList<>(list1);
list2.add(4);
```

In this case, Java creates a new copy of the list immediately, regardless of whether modifications are made, which can lead to higher memory usage and decreased performance.

Extensions

Swift's extensions allow developers to add new functionality to existing types, such as classes, structures, or protocols, without modifying their original implementation. This feature makes it simple to enhance types in a clean and modular way.

For example, consider adding a method to the 'Int' type that checks if a number is even:

```
extension Int {  
    var isEven: Bool {  
        return self % 2 == 0  
    }  
}  
  
let number = 42  
print(number.isEven) // Output: true
```

Java does not have an equivalent feature, so a utility method or wrapper class would be needed:

```
public static boolean isEven(int number) {  
    return number % 2 == 0;  
}  
  
int number = 42;  
System.out.println(isEven(number)); // Output: true
```

Swift's extension feature leads to more elegant and expressive code compared to Java in this example.

Custom Operators

Swift allows developers to define custom operators, providing flexibility and expressiveness in the language. Custom operators can be created for arithmetic, comparison, logical, and other operations, enhancing readability and simplifying complex expressions.

For example, consider defining a custom '**' operator for exponentiation:

```
infix operator **: MultiplicationPrecedence  
  
func **(base: Double, exponent: Double) -> Double {
```



```

        return pow(base, exponent)
    }

let result = 2.0 ** 3.0 // Output: 8.0

```

In Java, you would need to use the ‘Math.pow’ function directly, which may be less expressive:

```
double result = Math.pow(2.0, 3.0); // Output: 8.0
```

In summary, Swift’s simplicity and syntax, safety features like guard clauses, support for functional programming constructs, copy-on-write optimization, extensions, and custom operators contribute to writing simple, safe, and efficient code. These features enable developers to create high-performance serverless functions while maintaining readability and expressiveness.

Property Wrappers

Property wrappers in Swift are a powerful language feature that can significantly simplify code by encapsulating common patterns and behaviors. They allow developers to create reusable, composable, and declarative abstractions for property access patterns.

One prominent example of property wrappers is SwiftUI, a user interface toolkit for building applications. SwiftUI extensively uses property wrappers, such as ‘@State’, ‘@Binding’, and ‘@ObservedObject’, to manage state and data flow. These wrappers enable developers to create complex and reactive UIs with concise and expressive code.

Another instance where property wrappers are beneficial is the Swift ‘ArgumentParser’ library. This library provides a straightforward way to parse command-line arguments. By employing property wrappers like ‘@Option’, ‘@Argument’, and ‘@Flag’, developers can define command-line interfaces with minimal code, eliminating the need to manually handle argument parsing. This results in a more readable and maintainable codebase.

In the following Swift ‘ArgumentParser’ example, a ‘transform’ argument is used to define a URL option and validate the input:

```
import ArgumentParser

struct ExampleApp: ParsableCommand {
    @Argument(help: "Your name")

```

```

var name: String

@Option(help: "Your age")
var age: Int

@Argument(help: "URL of the PS (powersoft) Server", transform: urlTransformer)
var psURL: URL

func run() {
    print("Hello, \$(name)! You are \$(age) years old.")
    print("PS Server URL: \$(psURL)")
}
}

let urlTransformer: (String) -> URL = { str in
    guard let url = URL(string: str) else {
        fatalError("\$(str) is not a valid URL!")
    }
    return url
}

```

```
ExampleApp.main()
```

For comparison, let's look at similar functionality in Python using the 'argparse' library:

```

import argparse
import sys
from urllib.parse import urlparse

def url_transformer(str):
    url = urlparse(str)
    if not url.scheme or not url.netloc:
        sys.exit(f"{str} is not a valid URL!")
    return url

parser = argparse.ArgumentParser(description="Example command-line application")
parser.add_argument("name", help="Your name")
parser.add_argument("age", type=int, help="Your age")

```

```

parser.add_argument("psURL", type=url_transformer, help="URL of the PS (powersoft) Server")

args = parser.parse_args()

print(f"Hello, {args.name}! You are {args.age} years old.")
print(f"PS Server URL: {args.psURL}")

```

And in Java using the ‘picocli’ library:

```

import java.net.MalformedURLException;
import java.net.URL;
import picocli.CommandLine;
import picocli.CommandLine.Command;
import picocli.CommandLine.Option;
import picocli.CommandLine.Parameters;

@Command(name = "ExampleApp", description = "Example command-line application")
public class ExampleApp implements Runnable {
    @Parameters(index = "0", description = "Your name")
    private String name;

    @Option(names = {"-a", "--age"}, description = "Your age")
    private int age;

    @Parameters(index = "1", description = "URL of the PS (powersoft) Server", complete = true)
    private URL psURL;

    public static void main(String[] args) {
        int exitCode = new CommandLine(new ExampleApp()).execute(args);
        System.exit(exitCode);
    }

    @Override
    public void run() {
        System.out.printf("Hello, %s! You are %d years old.%n", name, age);
        System.out.printf("PS Server URL: %s%n", psURL);
    }

    public static class UrlConverter implements CommandLine.ITypeConverter<URL> {

```

```

    @Override
    public URL convert(String value) throws MalformedURLException {
        URL url = new URL(value);
        if (url.getProtocol() == null || url.getHost() == null) {
            throw new MalformedURLException(value + " is not a valid URL!");
        }
        return url;
    }
}

```

In the Python and Java examples, the code for validating and parsing the URL input is more verbose compared to the Swift version. The Swift `@Argument` property wrapper, combined with the `transform` argument, simplifies the code and enhances expressiveness.

In summary, Swift's property wrappers contribute to the language's simplicity and expressiveness, making it an attractive choice for serverless development. Their ability to provide powerful abstractions and code simplification is an advantage that might be more difficult or impossible to achieve in other languages.

4.2. Available Libraries and Frameworks

Swift has a growing ecosystem that is constantly evolving and expanding. However, it might not be as extensive as more established languages like Python, Java, and Node.js. This could affect the availability of libraries and frameworks needed for specific use cases in the context of FaaS. In this section, we will discuss some of the notable libraries and frameworks available for Swift, as well as some of the challenges developers may face in certain scenarios.

4.2.1 Web Development

One of the most prominent Swift web frameworks is Vapor, which allows developers to build web applications and APIs using Swift. While Vapor has gained popularity and offers many useful features, it comes with its own set of challenges when compared to popular frameworks or solutions available for Python, Node.js, and Java.

Popular Frameworks for Python, Node.js, and Java

In contrast to Swift’s Vapor, more established languages such as Python, Node.js, and Java offer a wide range of popular frameworks and libraries that make web development easier and faster. Some of these frameworks have been around for many years and have extensive documentation, community support, and a large ecosystem of plugins and extensions.

Python

- **Django:** A high-level web framework that promotes rapid development and clean, pragmatic design. It includes an ORM, authentication support, an admin interface, and many other features out-of-the-box [?].
- **Flask:** A lightweight web framework that provides flexibility for developers to choose their own components, such as databases and authentication systems [?].

Node.js

- **Express:** A minimal and flexible web application framework for Node.js that provides a robust set of features for web and mobile applications. Express is widely used and has a large number of plugins and middleware available [?].
- **Koa:** A next-generation web framework for Node.js, created by the team behind Express. Koa is designed to be more expressive and robust while being smaller and more lightweight [?].

Java

- **Spring Boot:** A widely-used framework that simplifies the development and deployment of Java-based web applications. Spring Boot provides built-in support for embedded servers, security, data access, and more [?].
- **JavaServer Faces (JSF):** A Java web application framework that simplifies building user interfaces for Java EE applications. JSF provides a component-based approach, allowing developers to build UIs by assembling pre-built components [?].

Example Use Cases

1. **User Authentication and Authorization:** When building a web application, it is common to require user authentication and authorization. Django includes built-in support for user authentication, while Express has the popular Passport middleware, and Spring Boot provides Spring Security. On the other hand, Vapor offers authentication support, but it might not be as mature or feature-rich as these other frameworks.
2. **Database Integration:** Many web applications require integration with databases. Django comes with a built-in ORM, while Flask has SQLAlchemy and Spring Boot offers JPA and Hibernate. In the Node.js ecosystem, Sequelize and TypeORM are popular choices for database integration. Vapor has its own ORM called Fluent, but it may lack the maturity, community support, and extensive documentation compared to the other solutions.
3. **Template Engines:** Rendering server-side templates is a common task in web development. Python's Django and Flask both offer built-in template engines, while Node.js's Express supports various templating engines like Pug and EJS. In Java, Thymeleaf is a popular template engine for Spring Boot applications. Vapor supports the Leaf template engine, but it may not have the same level of community support or plugin ecosystem as the alternatives.

In summary, while Swift's Vapor framework offers a powerful solution for web development, it may face challenges in terms of maturity, community support, and available plugins when compared to the popular frameworks and libraries available for Python, Node.js, and Java. Developers should consider the specific requirements of their serverless web applications and weigh the trade-offs between the available options.

Vapor and Swift Package Manager

Due to the way the Swift compiler and the Swift Package Manager currently work, resolving package dependencies can be time-consuming, as it happens sequentially. Even a boilerplate Vapor app requires the compilation of more than 1,500 files. Additionally, the Swift Package Manager has experienced stability issues, such as a bug related to updating dependencies from a specific branch of a Git repository. Although the bug has now been resolved, it demonstrates the growing pains Swift's ecosystem is experiencing.

Documentation and Community Support

As a newer language, Swift's documentation and community support might not be as comprehensive as more established languages. Developers may face challenges in finding appropriate resources or examples when working with specific libraries or frameworks in the context of FaaS. This could lead to slower development and increased reliance on trial and error to find solutions.

Despite these challenges, Swift's ecosystem continues to grow and improve, and many developers are contributing to its progress. With time and continued investment from the community, Swift is likely to become a more mature and stable language for serverless functions.

Example: Swift Package Manager Bug

One example that highlights Swift's infancy and lack of maturity for production use is a bug related to the Swift Package Manager. In the past, the Swift Package Manager had an issue where the package cache would not get invalidated for recent commits when a dependency was set to a branch of a Git repository (e.g., `.package(url: "https://github.com/andreas16700/OTModelSyncer_pub", branch: "main")`). This bug significantly hindered development, as developers were forced to resort to obscure workarounds to manage their dependencies.

In the specific case mentioned, the project was divided into several packages, and changes were committed frequently. Due to this bug, the development process became considerably more challenging. The developer had to run unit tests and use Docker containers to ensure operational consistency with Linux, which resulted in increased development time and effort.

Although the bug has now been fixed, it took more than three years since it first appeared on the Swift forums¹. This example demonstrates that while Swift is a powerful and promising language, it still faces challenges due to its relative immaturity compared to more established languages.

As the Swift ecosystem continues to grow and mature, it is likely that such issues will become less common. However, developers should be aware of the potential challenges they may face when adopting Swift for serverless functions and be prepared to invest additional time and effort to address them.

¹"Dependency on (very) active branch doesn't pull new commits", Swift Forums, January 2020 <https://forums.swift.org/t/dependency-on-very-active-branch-doesnt-pull-new-commits/33204>

4.2.2 Developer community and support

A robust developer community and available resources can contribute to the ease of development. While Swift has a strong community, the serverless aspect of it might not be as well-established as other languages.

4.2.3 Tooling and IDE support

Swift has great support in Xcode, which is the primary development environment for Apple platforms. However, developers who primarily work with other languages may not be familiar with Xcode. There is also support for Swift in other IDEs, such as Visual Studio Code, but the level of support may vary compared to languages with more extensive serverless development history.

4.2.4 Integration with serverless platforms

The ease of integrating Swift with serverless platforms like OpenWhisk, AWS Lambda, or Google Cloud Functions may impact the development experience. Consider the availability of templates, plugins, and other tools that facilitate serverless development and deployment.

4.2.5 Learning curve

The ease of development in a language also depends on an individual developer's familiarity and previous experience with that language. Swift is easy to learn for beginners, but developers who have never used Swift may need some time to become proficient.

4.2.6 Linux Support

Swift's support for Linux is relatively recent, and there are some features that are not available or have limited functionality due to the absence of the Objective-C runtime. Swift was designed to interoperate closely with Objective-C when it is present, but it was also designed to work in environments where the Objective-C runtime does not exist². This means that some features that depend on the Objective-C runtime are not available on Linux.

For example, when a Swift class on Apple's platforms is marked `@objc` or subclasses `NSObject`, you can use the Objective-C runtime to enumerate available meth-

²"Platform Support", swift.org <https://swift.org/about/#platform-support>

ods on an object or call methods using selectors. Such capabilities are absent on Linux because they depend on the Objective-C runtime³.

Developers might encounter unexpected limitations when developing serverless functions due to these differences. The exact features that are not available on linux are not well documented. While a program may compile and run fine on a Mac, it may either encounter a compiler-time error on linux or, albeit sparingly, crash at runtime. Developers may need to resort to writing unit tests and running them in Docker containers to ensure operational consistency between platforms.

An Example

While developing a crucial serverless function, compiling and deploying it raised no concerns. But trying to invoke it elicited an unexpected error.

```
aloizi04@kubel:~$ python3 invoke.py -p 8083 init syncModel syncModel_action.zip
{"ok":true}

aloizi04@kubel:~$ python3 invoke.py -p 8083 run
{"error":"command exited"}
```

Figure 4.1: Invoking the action using Apache’s `invoke.py` tool

Note: This is using the *invoke tool*⁴ provided by OpenWhisk for debugging runtimes.

Every action runs on a language runtime. A runtime is a docker image. Attaching to the docker container and trying to run the binary to get more clues, we can see the following issue:

```
root@d0478e2b14c9:/swiftAction/action/1/bin# ./exec
{"value": {}}
Received: {"value": {}}
Syncing model965
fetching source PS data..
Illegal instruction (core dumped)
root@d0478e2b14c9:/swiftAction/action/1/bin#
```

Figure 4.2: Crash witnessed by manually running the action executable in the runtime container

Due to the lack of Swift Linux IDEs and debuggers, not many options besides using `lldb` exist.

Building the program again in debug mode (for easier debugging) and investigating with `lldb`, an offending function is found and a breakpoint is set.

The issue seems to arise after invoking the `dataTask(with:)` function of Foundation’s `URLSession`. The networking part of Foundation made heavy use of

³ibid

⁴<https://github.com/apache/openwhisk/blob/master/tools/actionProxy/invoke.py>

```

32
33
34 func asyncData(with request: URLRequest)async throws -> (Data, URLResponse){
35     return try await withCheckedThrowingContinuation { continuation in
-> 36         let task = self.dataTask(with: request) { data, response, error in
37             fulfill(continuationFromCompletionHandler(continuation: continuation, data: data, response: response, error: error))
38         }
39         task.resume()
Target 0: (Action) stopped.
1: breakpoint set --name URLSession.dataTask
Breakpoint 4: 4 locations.
1: c
Process 2227 resuming
Process 2227 stopped
* thread #2, name = "Action", stop reason = breakpoint 4.2
  frame #0: 0x0000000000000000 libFoundationNetworking.dylib: FoundationNetworking.URLSession.dataTask(with: FoundationNetworking.URLRequest, completionHandler: (Swift.Optional<Foundation.Data>, Swift.Optional<FoundationNetworking.URLResponse>, Swift.Optional<Swift.Error>) -> ()) -> FoundationNetworking.URLSession.dataTask
libFoundationNetworking.dylib: FoundationNetworking.URLSession.dataTask(with: FoundationNetworking.URLRequest, completionHandler: (Swift.Optional<Foundation.Data>, Swift.Optional<FoundationNetworking.URLResponse>, Swift.Optional<Swift.Error>) -> ()) -> FoundationNetworking.URLSession.dataTask
-> 0x7ffff7536f0 <<8>; pushq %r0
0x7ffff7536f1 <<1>; pushq %r15
0x7ffff7536f2 <<3>; pushq %r14
0x7ffff7536f3 <<5>; pushq %r13
Target 0: (Action) stopped.
1: c
Process 2227 resuming
Process 2227 stopped
* thread #0, name = "Action", stop reason = signal SIGILL: illegal instruction operand
  frame #0: 0x0000000000000000 libFoundationNetworking.dylib: FoundationNetworking._HTTPURLProtocol.configureEasyHandle(for: FoundationNetworking.URLRequest, body: FoundationNetworking.URLSessionTask._body) -> () = 3281
libFoundationNetworking.dylib: FoundationNetworking._HTTPURLProtocol.configureEasyHandle(for: FoundationNetworking.URLRequest, body: FoundationNetworking.URLSessionTask._body) -> () = 3281
-> 0x7ffff740b75 <<5381>; ud2
0x7ffff740b77 <<5383>; ud2
0x7ffff740b79 <<5385>; ud2
0x7ffff740b7b <<5387>; ud2
Target 0: (Action) stopped.
1: c
Process 2227 resuming
Process 2227 exited with status = 4 (0x00000004)
1: c

```

Figure 4.3: Debugging with LLDB to find the cause of the crash

Objective-C and the Swift team, in the transition away from Objective-C, made a separate package called `FoundationNetworking` just for Linux. Many networking parts of `Foundation` are either poorly documented about their Linux support or silently unimplemented. The true cause of the above crash is unknown.

This example demonstrates a significant hurdle in the development process that might arise with no compiler warning, and made exceptionally more difficult with the sheer lack of any sort of feedback.

Debugging serverless applications is already difficult enough, and Swift FaaS developers should expect it to be even more difficult (in the case of Swift) as they may find themselves using `lldb` unexpectedly.

Swift's Linux support continues to evolve, and the community is working on addressing these limitations. However, developers should be aware of the potential challenges they may face when adopting Swift for serverless functions in a Linux environment and be prepared to invest additional time and effort to overcome them.

Chapter 5. Synchronization System Case Study

The main focus of this chapter is on a practical comparison between serverless and monolithic system implementations, specifically in the context of a synchronization system for a store’s logistics system and its Shopify store, simulated by two servers, PS and SH respectively.

5.1. System Overview

The synchronization system is designed to maintain a consistent state between the store’s logistics system and the Shopify store. It ensures that for every Item on PS, there exists an equivalent Variant on SH and that it is up-to-date, with PS being the source of truth. The synchronization task is mainly encapsulated in a single function, `syncModel(modelCode: String)`, which is deployed as an action on OpenWhisk in the serverless implementation and exposed as a route in the monolithic version.

API clients encapsulate CRUD operations for PS and SH. They handle operations such as fetching and updating items or stocks on PS and managing products, variants, and stocks on SH.

5.2. Experimental Setup

The experimental setup involved deploying the monolithic and serverless implementations on machines of type m510 on CloudLab in the Utah cluster. Benchmarks were conducted using increasing workloads to assess the performance of each system. A custom-built rate limiter was used to control the flow of requests to the systems.

5.3. Benchmarking Process

This section describes the workload and the main components involved in the benchmarking process. It also explains the methodology used in benchmarking the serverless and monolithic implementations.

5.3.1 Main Components

PS Server

The PS Server contains items and their stock count as shown in the following structures:

```
struct PSItem: Identifiable {  
    ...  
    let itemCode: String  
    let modelCode: String  
    var id: String { itemCode }  
    ...  
}  
  
struct PSStock: Identifiable {  
    let itemCode: String  
    var id: String { itemCode }  
    var stock: Int  
}
```

Many *Items* belong to one *Model*. A PSItem is identified by its `itemCode`, and a model is identified by a `modelCode`.

SH Server

The SH Server contains products and their stock count as shown in the following structures:

```
struct InventoryLevel: Identifiable {  
    let inventoryItemID: Int  
    var id: Int { inventoryItemID }  
    var stock: Int  
}  
  
struct SHVariant: Identifiable {  
    let id: Int  
    let productID: Int  
    let sku: String  
    let inventoryItemID: Int  
}
```

```

struct SHProduct: Identifiable {
    let id: Int
    let handle: String
    ...
    let variants: [SHVariant]
}

```

ModelSyncer

A *Model* from the PS Server corresponds to an *SHProduct* from the SH Server. A *Model*'s *PSItems* correspond to the respective *SHProduct*'s *SHVariant*. A *PSItem*'s stock (*PSStock*) corresponds to the respective *SHVariant*'s *InventoryLevel*. The goal of the *ModelSyncer* is to ensure that every model from the PS Server is reflected by an equivalent product on the SH Server (including stock listings).

5.3.2 Workload

A workload can be characterized by two variables:

1. Total number of models: The total number of models that should be generated on the PS Server. For each model, a number of items are generated ranging from 1 to 20.
2. Seed: Two numbers (*xSeed* and *ySeed*) that will be used for randomization. A pseudo-random number generator (PRNG) will be seeded with these numbers and will be used for all functions concerning randomization. This ensures that given these two variables the generated resources on the two servers will always be the same. Any reference to randomness, from now on, refers to pseudo-randomness provided by the PRNG.

5.3.3 Benchmarker

The Benchmarker does three main things:

1. Setup the two servers
2. Sync all models
3. Return metrics concerning step 2. Metrics include, among other things, the time it took, memory and space usage.

Setting up the servers

The Benchmarker will be referred to as 'B' to avoid repetition.

Generating models on PS Server ‘B’ sends a GET request to PS Server at the path ‘/generate/modelCount/xSeed/ySeed’. The PS Server generates `modelCount` models using the (`xSeed`, `ySeed`) seed.

Generating equivalent resource on SH Server For each model from the PS Server, the equivalent resource on the SH Server can be in one of three states:

1. Equivalent resources exist (SHProduct, SHVariant, InventoryListing) and are up to date.
2. Equivalent resources exist partially (SHProduct, SHVariants, InventoryLevels) and are not up to date. Partially exist means some items might not have an equivalent SHVariant on the SH Server. "Not up to date" means some properties of the resource on the SH Server might need updating (source of truth is always PS Server).
3. No equivalent resources exist for that model. That model does not exist on the SH Server. Its equivalent resources (SHProduct, SHVariants, InventoryLevels) have to be created from scratch.

SH Server has initially no data. N = total number of models generated on PS Server. P = number of models partially synced on SH Server (state 2). F = number of models fully synced on SH Server (state 3).

My apologies for the abrupt cut-off. Here is the continuation of the Benchmarking Process section:

‘B’ randomly generates the numbers P and F given the following constraints: $N > 0$ * $P + F < N$ * $0 \leq P \leq N$ * $0 \leq F < N$

The sum of the numbers of partially and fully synced models should not exceed the total number of models. All models could be partially synced, but all models should not be fully synced as there would be no work to be done.

‘B’ requests $P + F$ random models from the PS Server. Then, ‘B’ constructs the partially and fully synced products from the P and F models, respectively, along with their respective stocks. The RNG is used to generate random data such as IDs and stock counts. ‘B’ finally sends this data to the SH Server on the route ‘batchProductsAndStocks’.

At this point, the two servers are set up and ready to run any benchmarks to sync any models.

Running a workload

The process of running a workload is very similar between the serverless and the monolithic implementations. The only way they differ is in the ‘syncModel’ function.

To encapsulate this behavior and simplify the benchmarking, the following protocol is defined:

```
protocol WorkloadRunner {
    init(psURL: URL, shURL: URL, msDelay: Int?)
    static var name: String { get }
    var psClient: MockPsClient { get }
    var shClient: MockShClient { get }
    func runSync(sourceData: SourceData) async throws -> (Int, Int, [UInt64])
}
```

Any type that fulfills these requirements can then be used with the Benchmark and get results.

The ‘runSync’ function takes some source data (the current data on the two servers) and returns S, F, L where S is the number of successful syncs, F the number of failed syncs, and L is an array that contains the latency observed for each sync (the amount of time it took for a single model sync to complete).

This allows the Benchmark to easily get comparative results for a range of workload sizes for each ‘RunnerType’. For instance, for a given workload, it can easily set up the servers and run an implementation (make it sync every model):

```
static func runOnce(workload: Workload, runner: WorkloadRunner) async throws -> (Int, Int, [UInt64]) {
    let name = type(of: runner).name
    print("Setting up servers for ", name)
    await setUpServers(for: workload)
    print("Retrieving source data...")
    let source = await getSourceData()
    print("Running..")
    var (successes, fails, durations) = (0, 0, [UInt64].init(repeating: 0, count: 100))
    let duration = try await SuspendingClock().measure {
        (successes, fails, durations) = try await runner.runSync(sourceData: source)
    }
    print("\(name) took \(duration). Had \(fails) fails and \(successes) successes")

    print("Resetting servers' state..")
    let _ = await runner.psClient.reset()
    let _ = await runner.shClient.reset()
    print("Reset both servers.")
}
```

```

    return (name, duration, successes, fails, durations)
}

```

The above function is for running one workload on one runner. We can leverage this to easily run the benchmark for every ‘RunnerType‘:

```

func runAll(minModelCount: Int, totalModelCount, increments: Int) {
    let workloadSizes = stride(from: minModelCount, to: totalModelCount + 1, by: increments)
    let resultsFileName = "bench_\(workload.totalModelCount)_\((runners.map { type(of: $0) }.joinToString(", "))"
    let writer = initializeCSV(name: resultsFileName)
    for modelsCount in workloadSizes {
        var times: [Duration] = .init()
        var successes: [Int] = .init()
        var fails: [Int] = .init()
        var latencies: [Stats] = .init()
        let (name, time, succ, fail, lats) = try await Self.runOnce(workload: workload, modelsCount: modelsCount)
        print(name, "took \((time)")
        times.append(time)
        successes.append(succ)
        fails.append(fail)
        latencies.append(.init(from: lats)!)
        addResults(writer: writer, modelsCount: modelsCount, times: times, succ: succ, fail: fail, lats: lats)
    }
}

```

The above function ensures that for every workload size, every ‘RunnerType‘ gets to do the exact same type of work as the environment is exactly the same (thanks to using the same RNG seeds). The results are written to a CSV file. The technicalities of the CSV writing are beyond the scope of this chapter.

5.4. Results and Discussion

In comparison, the serverless implementation showed significantly slower performance, ranging from 4 to 10 times slower than the monolithic one. Even when using the rate limiter set at 70ms, the serverless implementation took 120ms, significantly slower than the monolithic implementation, which took 25ms.

Despite utilizing 18 machines for executing actions, the serverless approach did not show any clear benefits. This may be attributed to the lack of support for

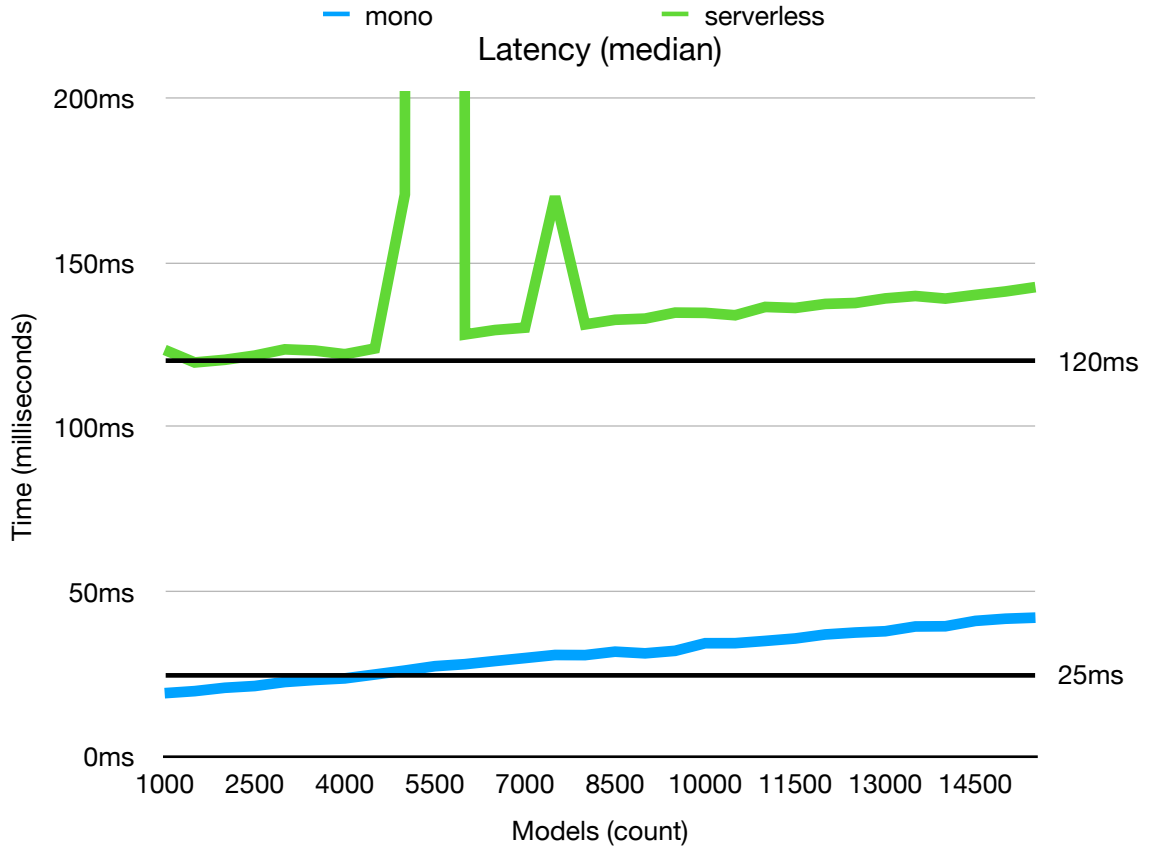


Figure 5.1: Rate-limited comparison between serverless and monolithic implementations

"intra-concurrency" in OpenWhisk runtimes, excluding NodeJS. This limitation significantly affects the scaling capabilities of the serverless implementation, which is a crucial aspect of the serverless or FaaS promise.

5.5. Improvements and Future Work

There are potential avenues for improvement in the serverless system. Notably, updating the Go proxy used by all OpenWhisk runtimes to support intra-concurrency could allow all language runtimes, including Swift, to support it, potentially reducing the execution latency.

5.6. Conclusion

The case study findings contribute to the overall conclusion of this thesis, suggesting that the benefit of migrating to a serverless implementation is not always evident and should be carefully assessed for each workflow. The case study also highlights the importance of runtime support for intra-concurrency in realizing the full potential

of serverless systems. Notably, the Swift runtime was updated to the latest version to leverage its native `async/await` features, which played a significant role in the serverless implementation.