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Functional Go

an easier introduction to functional programming

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Summary

(in Deutsch)

Abstract

(in Englisch)

Preface

Stellt den persönlichen Bezug zur Arbeit dar und spricht Dank aus.

Contents

1 Introduction

1.1 Learning Functional Programming

When Javascript and Python started to take off around 2010[1], they also brought rise to a lot of concepts borrowed from functional programming. Since then, many new multi-paradigm languages have appeared and gotten more popular, as for example Go, Rust, Kotlin and Dart. Most of the languages mentioned support an imperative, object-oriented, as well as a functional programming style. Rust, being the 'most popular programming language'for 4 years in a row (2016–2019), has been significantly influenced by functional programming languages[2] and borrows a lot of functional concepts in idiomatic Rust code.

Learning a functional programming language increases fluency with these concepts and teaches a different way to think and approach problems when programming. For those reasons, and many more, a lot of programmers advocate learning a functional programming language.

Though the exact definition of what a *purely* functional language consists of remains a controversy[3], the most popular, pure functional programming language seems to be Haskell[4].

1.2 Haskell

Haskell, the *lingua franca* amongst functional programmers, is a lazely-evaluated, purely functional programming language. While Haskell's strengths stem from all it's features like type classes, type polymorphism, purity and more, these features are also what makes Haskell famously hard to learn[5][6][7][8].

Beginner Haskell programmers face a very distinctive challenge in contrast to learning a new, non-functional programming language: Not only do they need to learn a new language with an unusual syntax (compared to imperative or object-oriented languages), they also need to change their way of thinking and reasoning about problems.

For example, the renowned quicksort-implementation from the Haskell Introduction Page[9]:

```
quicksort :: Ord a => [a] -> [a]
quicksort []     = []
quicksort (p:xs) = (quicksort lesser) ++ [p] ++ (quicksort greater)
    where
        lesser  = filter (< p) xs
        greater = filter (>= p) xs
```

While this is only a very short and clean piece of code, these 6 lines already pose many challenges to non-experienced Haskellers;

- The function's signature with no 'fn' or 'func' statement as they often appear in imperative languages
- The pattern matching, which would be a 'switch' statement or a chain of 'if / else' conditions
- The deconstruction of the list within the pattern matching
- The functional nature of the program, passing '(< p)' (a function returning a function) to another function
- The function call to 'filter' without paranthesised arguments and no clear indicator at which arguments it takes and which types are returned

Though some of these points are also available to programmers in imperative or object-oriented languages, the cumulative difference is not to underestimate and adds to Haskell's steep learning curve.

1.3 Goals

The goal is to solve the issue of the first steps in functional programming. Learning a new paradigm and syntax at the same time can be daunting and discouraging for novices. By using a modern, multi-paradigm language with a clear and familiar syntax, the functional programming beginner should be able to focus on the paradigm first, and then change to a language like Haskell to fully get into functional programming.

To ease the learning curve of functional programming, this thesis will consist of two parts:

- Make a multi-paradigm language support functional programming as much as needed. The criteria for this language are:
  - Easy, familiar syntax
  - Be statically typed, as this makes it easier to reason about a program
  - Have support for functional programming features like first class functions, currying and partial application
- Create a linter that checks code on its functional purity. For this, some rules will have to be curated to define what pure functional code is.

It s not the goal to create a production-ready functional language, so runtime and performance requirements can be ignored.

1.4 Why Go

The language of choice for this task is Go, a statically typed, garbage-collected programming language designed at Google in 2009[10]. With its strong syntactic similarity to C, it should be familiar to most programmers. Go is an extremely verbose language with almost no syntactic sugar. This makes it a perfect fit to grasp the concepts and trace the inner workings of functional programming.

There are, however, a few downsides of using Go:

- No polymorphism. Go 2 will likely have support for polymorphism, but at the time of writing, there is no implementation available.
- Missing implementations for common functions like 'map', 'filter', 'reduce' and more.
- No list implementation. Go has 'slices', which are 'views' on arrays, but no list datatype.

1.4.1 Go Slices

Go's Slices can be viewed as an abstraction over arrays, to mitigate some of the weaknesses of arrays compared to lists.

> *Arrays have their place, but they're a bit inflexible, so you don't see them too often in Go code. Slices, though, are everywhere. They build on arrays to provide great power and convenience.[11]*

Slices can be visualised as a 'struct' over an array:

```
// NOTE: this type does not really exist, it
// is just to visualise how they are implemented.
type Slice struct {
    // the underlying "backing store" array
    array *[]T
    // the length of the slice / view on the
    //array
    len   int
    // the capacity of the array from the
    // starting index of the slice
    cap   int
}
```

With the 'append' function, elements can be added to a slice. Should the underlying array not have enough capacity left to store the new elements, a new array will be created and the data from the old array will be copied into the new one. This happens transparently to the user.

Using Slices

'head', 'tail' and 'last' operations can be done with index expressions:

```
// []<T> initialises a slice, while [n]<T> initialises an
// array, which is of fixed length n. One can also use `...'
// instead of a natural number, to let the compiler count
// the number of elements.
s := []string{"first", "second", "third"}
head := s[0]
tail := s[1:]
last := s[len(s)-1]
```

Adding elements or joining slices is achieved with 'append':

```
s := []string{"first", "second"}
s = append(s, "third", "fourth")
t := []string{"fifth", "seventh"}
```

```
s = append(s, t...)
// to prepend an element, one has to create a
// slice out of that element
s = append([]string{"zeroth"}, s...)
```

Append is a variadic function, meaning it takes n elements. If the slice is of type $[]<T>$, the appended elements have to be of type $<T>$.

To join two lists, the second list is expanded into variadic arguments.

More complex operations like removing elements, inserting elements in the middle or finding elements in a slice require helper functions, which have also been documented in Go's Slice Tricks[12].

What is missing from Slices

This quick glance at slices should clarify that, though the runtime characteristics of lists and slices can differ, from a usage standpoint, what is possible with lists is also possible with slices.

However, what is missing from Go's slices are a lot of the classical list 'helper' functions. In a typical program written in a functional language, lists take a central role. This results in a number of helper functions[13] that currently do not exist in Go and would need to be implemented by the programmer. With no support for polymorphism, the programmer would need to implement a function for every slice-type that is used. The type `[]int` (read: a slice of integers) differs from `[]string` which means that a possible 'map' function would have to be written once to support slices of integers, once to support slices of strings, and a combination of these two:

```
func mapIntToInt(f func(int) int, []int) []int
func mapIntToString(f func(int) string, []int) []string
func mapStringToInt(f func(string) int, []string) []int
func mapStringToString(f func(string) string, []string) []string
```

With 7 base types (eliding the different 'int' types like 'int8', 'uint16', 'int16', etc.), this would mean $7^2 = 49$ map functions just to cover these base types. Counting the different numeric types into that equation (totally 19 distinct types[14]), would grow that number to $19^2 = 361$ functions.

Though this code could be generated, it leaves out custom user-defined types, which would still need to be generated separately.

To mitigate this point, the most common list-operations (in Go slice-operations) will be added to the compiler, so that the programmer can use these functions on every slice-type.

1.5 Existing Work

With Go's support of some functional aspects, patterns and best practices have emerged that relate to functional programming. For example, in the *net/http* package of the standard library, the function

```
func HandleFunc(pattern string, handler func(ResponseWriter, *Request))
```

is used to register functions for http server handling:

```
func myHandler(w http.ResponseWriter, r *http.Request) {
    // Handle the given HTTP request
}

func main() {
    // register myHandler in the default ServeMux
    http.HandleFunc("/", myHandler)
    http.ListenAndServe(":8080", nil)
}
```

[15]

Using functions as function parameters or return types is a commonly used feature in Go, not just within the standard library.

A software design pattern that has gained popularity is 'functional options'. The pattern has been outlined in Dave Cheney's blog post 'Functional options for friendly APIs' and is a great example on how to use the support for multiple paradigms.

To give a quick example of how functional options look like and are used:

```go
package webserver

type Server struct {
    Timeout time.Duration
    Port int
    ListenAddress string
}

type Option func(*Server)

func Timeout(d time.Duration) Option {
    return func(s *Server) {
        s.Timeout = d
    }
}
func Port(p int) Option {
    return func(s *Server) {
        s.Port = p
    }
}

func New(opts ...Option) *Server {
    // initialise the server with the default values
    s := &Server{
        Timeout: 500*time.Millisecond,
        Port: 0, // uses a random port on the host
        ListenAddres: "http://localhost",
    }
    // apply all options
    for _, opt := range opts {
        opt(s)
    }
    return s
}

// usage examples from outside the package:
s := webserver.New() // uses all the default options
s := webserver.New(webserver.Timeout(time.Second), webserver.Port(8080))
```

Dave Cheney's summary on functional options is thus:

> *In summary*
>
> - *Functional options let you write APIs that can grow over time.*
> - *They enable the default use case to be the simplest.*
> - *They provide meaningful configuration parameters.*
> - *Finally they give you access to the entire power of the language to initialize complex values.*
>
> *[16]*

While this is a great example of what can be done with support for functional concepts, a purely functional approach to Go has so far been discouraged by the core Go team, which is understandable for a multi-paradigm programming language. However, multiple developers have already researched and tested Go's ability to do functional programming.

Functional Go?

In his talk 'Functional Go'[17], Francesc Campoy Flores analysed some commonly used functional language features in Haskell and how they can be ported with Go. Ignoring speed and stackoverflows due to non-existent tail call optimisation[18], the main issue was with the type system and the missing polymorphism.

go-functional

In July 2017, Aaron Schlesinger, a Go programmer for Micosoft Azure, gave a talk on functional programming wit Go. He released a repository[19] that contains 'core utilities for functional Programming in Go'. The project is currently unmaintained, but showcases functional programming concepts like currying, functors and monoids in Go. In the 'README' file of the repository, he also states that:

> *Note that the types herein are hard-coded for specific types, but you could use code generation to produce these FP constructs for any type you please! [20]*

1.6 Work to be done

To conclude, the work that has to be done for this thesis is:

- Define which 'standard' list functions are most commonly used in functional programming
- Implement some of them into the compiler
  - at least one of these functions needs to have complete type-checking
  - demonstrate some usage examples for these functions
- Research 'rules' for pure functional programming
  - for example, this could be exact definitions of immutability and purity
- Add these rules to a checker. This could be an already available tool like 'go vet', or a newly developed, purpose-built utility

2 Methodology

2.1 Slice Helper Functions

2.1.1 Choosing the functions

The first task is to implement some helper functions for slices, as they are present for lists in Haskell. To decide on which functions will be implemented, popular Haskell repositories on Github have been analysed. The popularity of repositories was decided to be based on their number of stars. Out of all Haskell projects on Github, the most popular are[21]:

- Shellcheck (koalaman/shellcheck[22]): A static analysis tool for shell scripts
- Pandoc (jgm/pandoc[23]): A universal markup converter
- Postgrest (PostgREST/postgrest[24]): REST API for any Postgres database
- Semantic (github/semantic[25]): Parsing, analyzing, and comparing source code across many languages
- Purescript (purescript/purescript[26]): A strongly-typed language that compiles to JavaScript
- Compiler (elm/compiler[27]): Compiler for Elm, a functional language for reliable webapps
- Haxl (facebook/haxl[28]): A Haskell library that simplifies access to remote data, such as databases or web-based services

In these repositories, the number of occurrences of popular list functions have been counted. The analysis does not differentiate between different kind of functions. For example, 'fold' includes all occurrences of 'foldr', 'foldl' and 'foldl'́. Also, the analysis has not been done with any kind of AST-parsing. Rather, a simple 'grep' has been used to find matches. This means that it is likely to contain some mismatches, for example in code comments. All in all, this analysis should only be an indicator of what functions are used most.

Running the analysis on the 7 repositories listed above, searching for a number of preselected list functions, indicates that the most used functions are ':' (cons), 'map' and 'fold', as shown in table 2.1.

Table 2.1: Occurrences of list functions1

map	1241
':' (cons)	1177
fold	610
filter	262
reverse	154
take	104
drop	81
maximum	53
sum	44
zip	38
product	15
minimum	10
reduce	8

1 2

Based on this information, it has been decided to implement the map, cons and fold functions into the Go compiler.

2.1.2 The Go Compiler

The Go programming language is defined by its specification[29], and not it's implementation. As of Go 1.14, there are two major implementations of that specification; Google's

[1] The cons function (':') is overrepresented in this list, as it can also be used to deconstruct lists within pattern matching. Filtering these occurrences would need a more advanced algorithm. However, even if $\frac{3}{4}$ of these usages are used in pattern matching, the cons function would still be in the top 3.

[2] The map function listed here also includes occurrences of 'fmap'. A more detailed look at the data shows that there are 632 occurrences of 'fmap', which means that 'fmap' and 'map' are used equally as often. As 'fmap' however requires some kind of implementation for an 'iterable', it is out of scope for this paper.

self-hosting compiler toolchain [3] 'gc', which is written in Go, and 'gccgo', a frontend for GCC, writen in C++.

When talking about the Go compiler, what's mostly referred to is 'gc'. [4]

A famous, although not completely correct story tells about Go being designed while a C++ program was compiling[30]. This is why one of the main goals when designing Go was fast compilation times:

> *Finally, working with Go is intended to be fast: it should take at most a few seconds to build a large executable on a single computer. To meet these goals required addressing a number of linguistic issues: an expressive but lightweight type system; concurrency and garbage collection; rigid dependency specification; and so on. These cannot be addressed well by libraries or tools; a new language was called for.[31]*

This is why Go has taken some measures to to combat slow compilation times. According to Rob Pike, one of the creators of Go, Go's compiler is not notably fast, but most other compilers are slow:

> *The compiler hasn't even been properly tuned for speed. A truly fast compiler would generate the same quality code much faster.[32]*

The language design does have some limitations however to lower compilation times. In general, Go's dependency resolution is simpler compared to other languages, for example by not allowing circular dependencies. Furthermore, compilation is not even attempted if there are unused imports or unused declarations of variables, types and functions. This leads to less code to compile and in turn shorter compilation times. Another reason is that 'the 'gc' compiler is simpler code compared to most recent compilers'[32].

Compiling Go programs with the standard 'gc' compiler can be split into four phases:

Parsing Go programs

The first phase of compilation is parsing Go programs into a syntax tree. This is done by tokenizing the code ('lexical analysis' - the 'lexer'), parsing ('syntax analysis' - the 'parser') it and then constructing a syntax tree (AST) for each source file[5].

[3] This is what most often is referred to as 'the Go compiler'.
[4] 'gc' stands for 'Go Compiler', and not 'Garbage Collection' ('GC').
[5] Technically, the syntax tree is a syntax DAG[33]

In comparison to most production-level languages, Go can be parsed without a symbol table. It has been designed to be easy to parse and analyse, which makes the Go parser simple in it's design[34].

Type-checking and AST-transformation

The second phase of compilation starts by converting the 'syntax' package's AST, created in the first phase, to the compiler's AST representation. This is due to historical reasons, as the 'gc's AST definition was carried over from the C implemenation.

After the conversion, the AST is type-checked. Within the type-checking, there are also some additional steps included like 'declared and not used' and determining wheter a function terminates.

After type-checking, some transformations are applied on the AST. This includes, but is not limited to, eliminating dead code, inlining function calls and escape analysis. What is also done in the transformation phase is rewriting builtin function calls, replacing for example a call to the builtin 'append' with the necessary AST structure and rutime-calls to implement its functionality.

SSA

In the third phase, the AST is converted to SSA form. SSA is 'a lower-level intermediate representation with specific properties that make it easier to implement optimizations and to eventually generate machine code from it'[35].

The conversion consists of multiple 'passes' through the SSA that apply machine-independent rules to optimise code. These generic rewrite rules are applied on every architecture and thus mostly concern expressions (e.g. replace expressions with constant values and optimise multiplications), dead code elimination and removal of unneeded nil-checks.

Generating machine code

Lastly, in the fourth phase of the compilation, machine-specific SSA optimisations are applied, including, but not limited to:

– Rewriting generic values into their machine-specific variants (for example, on amd64, combining load-store operations)

- Another dead-code elimination pass
- Pointer liveness analysis
- Removing unused local variables

After generating and optimising the SSA form, the code is passed to the assembler, which replaces the so far generic instructions with architecture-specific machine code and writes out the final object file. [35]

2.1.3 Built-in functions

What has only been discussed very briefly in chapter 2.1.2 are built-in functions. The language specification defines what built-in functions are and which built-in functions should exist:

> *Built-in functions are predeclared. They are called like any other function but some of them accept a type instead of an expression as the first argument.*
>
> *The built-in functions do not have standard Go types, so they can only appear in call expressions; they cannot be used as function values.[36]*

As Go does not have generics (polymorphism), functions that return a variable but concrete type have to be built-in into the language itself.

For example, if 'append' would not exist as a built-in, there would be two options to work around that.

One option would be that 'append' would take and return empty interfaces (`interface{}`). However, 'the empty interface says nothing'[37]. The declaration of 'append' would be:

```
func append(slice []interface{}, elem ...interface{}) {}interface
```

This function header does not say anything about it's types, which would mean that they would need to be checked at runtime and handled gracefully. It would also require the caller to do a type assertion after every call:

```
s := []string{"hello"}
s = append(s, "world").([]string)
```

It also does not specify that the slice's element type would need to be equal to the appended element. Instead, this would need to be a convention.

The other option would be to specify a function upon each type, meaning:

```
func appendInt(slice []int, elem ...int} []int
func appendString(slice []string, elem ...string} []string
...
```

Which is not only extremely verbose, but also misses any custom user-defined types.

For this reason, the helper function that should be implemented need to be implemented within the compiler, as built-in functions.

2.1.4 Map

The most used function in Haskell is map. The table 2.1 counts 1200 occurrences of map, although 600 of those occurrences are from fmap. fmap is the generic version of map: while map only works on lists, fmap works on every type that implements the 'Functor' typeclass[6], including tuples, 'Maybe' and lists. 'In practice a functor represents a type that can be mapped over.'[38] A common analogy for functors are 'boxes'. A functor behaves like a box where a value can be put into and taken out again. For lists, the operation of 'taking out' elements means processing each value one by one. For 'Maybe', it means 'unpacking' the concrete value and processing it, and if there is no concrete value, returning 'Nothing' instead.

map (and fmap) is one of the most useful higher-order functions:

map

> *returns a list constructed by appling a function (the first argument) to all items in a list passed as the second argument[39].*

Some usage examples of map can be found at 2.1.

Source Code 2.1: Example usage for map and fmap

[6] typeclasses in Haskell are what would be interfaces in imperative and object-oriented languages

```
Prelude> :t map
map :: (a -> b) -> [a] -> [b]
Prelude> :t fmap
fmap :: Functor f => (a -> b) -> f a -> f b
Prelude> map (*3) [1,2,3]
[3,6,9]
Prelude> fmap (*3) [1,2,3]
[3,6,9]
Prelude> map (++ " world") ["hello","goodbye"]
["hello world","goodbye world"]
Prelude> map show [1,2,3]
["1","2","3"]
```

Due to missing polymorphism, map cannot be implemented as easily in Go. While a specific definition of map would be `func map(f func(int) string, []int) []string`, this definition would only hold true for the specific types `int` and `string`. A more generic definition, similar to append, would be `func map(f func(Type1) Type2, []Type1) []Type2`. For this to work, the function has to be implemented as a builtin into the compiler.

As there is already a 'map' token in the Go compiler (for the map data type), the function will be called 'fmap'. However, it only works on slices. This is due to the absence of an 'iterator'-like concept. The 'range' clause, used with 'for' loops, only works on slices and maps - both are builtin data types. It does not work on custom data structures, which would make the implementation a far bigger task. Nonetheless, to avoid possible naming confusions, the 'map' function in Go will be called 'fmap'.

In Go, the usage of 'fmap' should result in making the program 2.2 behave as shown.

Source Code 2.2: Example usage of map in go

```
package main

import (
        "fmt"
        "strconv"
)

func main() {
        fmt.Printf("%#v", fmap(strconv.Itoa, []int{1, 2, 3}))
}
```

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```
$> fgo run .
[]string{"1", "2", "3"}
```

2.1.5 Cons

The name cons has been introduced by LISP, where it describes a record structure containing two components called the 'car' (the 'contents of the address register'), and the 'cdr' ('content of decrement register'). Lists are built upon cons cells, where the 'car' stores the element and 'cdr' a pointer to the next cell - the next element of the list. This is why in Lisp, `(cons 1 (cons 2 (cons 3 (cons 4 nil))))` is equal to `(list 1 2 3 4)`. This list is also visualised in picture 2.1.

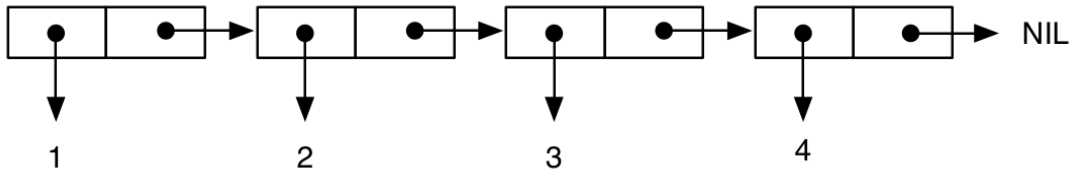

Figure 2.1: Cons cells forming a list[41]

The cons operator thus prepends an element to a list, effectively allocating a variable that contains the newly added element and a pointer to the 'old' list. As a result, prepending to a list is computationally cheap, needing one allocation and one update.

In Haskell, the 'name' of the cons function is the ':' operator. In Go, names for identifiers (which includes function names) underlie a simple rule:

> *An identifier is a sequence of one or more letters and digits. The first character in an identifier must be a letter.[42]*

This rule forbids a function to be named ':'. Instead, the function could be named 'cons'. However, Go already has a function to add to the end of a slice, 'append'. Thus, adding to the beginning of a slice will be named 'prepend'. Using prepend is very similar to append, an example can be found at 2.3

[7] Printf's first argument, the verb '%#v', can be used to print the type ('#') and the value ('v') of a variable[40].

Source Code 2.3: Example usage of prepend in go

```
package main

import (
        "fmt"
        "strconv"
)

func main() {
        fmt.Printf("%#v", prepend(0, []int{1, 2, 3}))
}
```

```
$> fgo run .
[]int{0, 1, 2, 3}
```

2.1.6 Fold

Fold, sometimes also named 'reduce' or 'aggregate' is another higher-order function that is very commonly used in functional programming.

> *analyze a recursive data structure and through use of a given combining operation, recombine the results of recursively processing its constituent parts, building up a return value.[43]*

The family of fold functions in Haskell consist of three different implementations of that definition: 'foldr', 'foldl' and 'foldl'́. The difference between foldr and foldl is hinted at their function headers:

Source Code 2.4: Function headers of the fold functions

```
Prelude Data.List> :t foldr
foldr :: Foldable t => (a -> b -> b) -> b -> t a -> b
Prelude Data.List> :t foldl
foldl :: Foldable t => (b -> a -> b) -> b -> t a -> b
```

The argument with type ‘b’ is passed as the first argument to the foldl function, and as the second argument to foldr. As can be seen in the illustrations of foldl and foldr in 2.2, the evaluation order of the two functions differ.

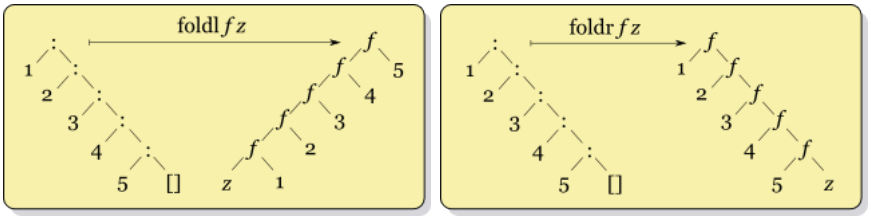

Figure 2.2: Folds illustrated[43]

This is most obvious when using an example where the function is not associative:

Source Code 2.5: foldr and foldl execution order

```
foldr (-) 0 [1..7]
1 - (2 - (3 - (4 - (5 - (6 - (7 - 0)))))) = 4
foldl (-) 0 [1..7]
((((((0 - 1) - 2) - 3) - 4) - 5) - 6) - 7 = -28
```

In foldl, the accumulator (‘0’) is added to the left end of the list (prepended), while with foldr, the accumulator is added to the right end. For associative functions (e.g. ‘+’) this does not make a difference, it does however for non-associative functions, as can be seen in the example 2.5.

The difference between foldl and foldl’ is more subtle:

> *foldl and foldl’ are the same except for their strictness properties, so if both return a result, it must be the same.[44]*

The strictness property is only relevant if the function is lazy in its first argument, meaning that foldl builds up an execution path, while foldl’ executes the instructions while traversing it:

Source Code 2.6: foldl and foldl’ strictness[44]

```
> (?) :: Int -> Int -> Int
> _ ? 0 = 0
> x ? y = x*y
>
```

```
> list :: [Int]
> list = [2,3,undefined,5,0]
>
> foldl (?) 1 list
foldl (?) 1 [2,3,undefined,5,0] -->
foldl (?) (1 ? 2) [3,undefined,5,0] -->
foldl (?) ((1 ? 2) ? 3) [undefined,5,0] -->
foldl (?) (((1 ? 2) ? 3) ? undefined) [5,0] -->
foldl (?) ((((1 ? 2) ? 3) ? undefined) ? 5) [0] -->
foldl (?) (((((1 ? 2) ? 3) ? undefined) ? 5) ? 0) [] -->
((((1 ? 2) ? 3) ? undefined) ? 5) ? 0 -->
0

> foldl' (?) 1 list
foldl' (?) 1 [2,3,undefined,5,0] -->
    1 ? 2 --> 2
foldl' (?) 2 [3,undefined,5,0] -->
    2 ? 3 --> 6
foldl' (?) 6 [undefined,5,0] -->
    6 ? undefined -->
*** Exception: Prelude.undefined
```

To keep things simpler, Go will only have its versions of foldl and foldr, which will both be strict - the Haskell counterparts would thus be foldr and foldl'.[8] The usage of these fold-functions is equal to the Haskell versions, where foldl's arguments are switched in order.

Source Code 2.7: Example usage of foldr and foldl in go

```
package main

import "fmt"

func main() {
        fmt.Printf("%v\n", foldr(func(x, y int) int { return x - y },
        ↪  100, []int{10, 20, 30}))
        fmt.Printf("%v\n", foldl(func(x, y int) int { return x - y },
        ↪  100, []int{10, 20, 30}))
```

[8] If the behaviour from the normal foldl function is required, a workaround can be applied in th Go version. See appendix 2

```
}
```

```
$> fgo run .
-80
40
```

2.2 Functional Check

3 Implementation

3.1 Implementing the new built-in functions

3.1.1 Required Steps

Adding a builtin function to the Go language requires a few more steps than just adding support within the compiler. While it would technically be enough to support the translation between Go code and the compiled binary, there would be no visibility for a developer that there is a function that could be used. For a complete implementation, the following steps are necessary:

- Adding the GoDoc[45] that describes the function and it's usage
- Adding type-checking support in external packages for tools like Gopls[46]
- Adding the implementation within the internal[1] package of the compiler
  - Adding the AST node type
  - Adding type-checking for that node type
  - Adding the AST traversal for that node type, translating it to AST nodes that the compiler already knows and can translate to builtin runtime-calls or SSA

The go source code that is relevant for this thesis can be classified into three different types. One is the godoc - the documentation for the new built-in functions. The other two are the 'public' and the 'private' implementation of these builtins.

The 'private' implementation is everything that is located within the *src/cmd/compile/internal* package[47]. It can only be used by the package in *src/cmd/compile*, which contains the implementation of the compiler itself. When calling `go build .`, the compiler is invoked indirectly. To directly invoke the compiler, `go tool compile` can be used. The compile tool gets compiled from the main package located in *src/cmd/compile*, which in turn uses the internal package.

[1] "An import of a path containing the element "internal" is disallowed if the importing code is outside the tree rooted at the parent of the 'internal' directory."[47]

Everything that is not in *src/cmd/compile* is referred to as the 'public' part of the compiler in this thesis. The 'public' parts are used by external tools, for example Gopls, for type-checking, source code validation and analysis.

3.1.2 Adding the GoDoc

In Go, documentation is generated directly from comments within the source code [45]. This also applies to builtin functions in the compiler, which have a function stub to document their behaviour[48], but no implementation, as that is done in the compiler[49].

The documentation for builtins should be as short and precise as possible. The usage of 'Type' and 'Type1' has been decided based on other builtins like 'append' and 'delete'. The function headers are derived from their Haskell counterparts, adjusted to the Go nomenclature.

Source Code 3.1: Godoc for the new built-in functions

```
// ...
// The prepend built-in function prepends an element to the start of
// the slice.  As slices do not have any capacity in the beginning,
// this function always results in an expensive copy of the original
// slice. Prepend returns the updated slice. It is therefore necessary
// to store the result of prepend, often in the variable holding the
// slice itself.
func prepend(elem Type, slice []Type) []Type

// The fmap built-in function maps a slice of elements from one type to
// a slice of elements of another type, using the given function.
// The returned slice always has the same number of elements as the
// source slice.
func fmap(fn func(Type) Type1, slice []Type) []Type1

// The fold built-in functions fold over a slice of elements with the
// given function. It takes init, the second argument, and the last
// item of the list and applies the function, then it takes the
// penultimate item from the end and the result, and so on.
// foldr and foldl differ in their evaluation order - foldr starts
// at the last, foldl at the first element of the slice.
func foldr(fn func(Type, Type1) Type1, acc Type1, slice []Type) Type1
func foldl(fn func(Type1, Type) Type1, acc Type1, slice []Type) Type1
```

```
// ...
```

3.1.3 Public packages

> *Note that the ‘go/*‘ family of packages, such as ‘go/parser‘ and ‘go/types‘, have no relation to the compiler. Since the compiler was initially written in C, the ‘go/*‘ packages were developed to enable writing tools working with Go code, such as ‘gofmt‘ and ‘vet‘.[35]*

To enable tooling support for the new built-in functions, they have to be registered in the ‘go/*’ packages. The only package that is affected by new builtins is ‘go/-types’.

In the ‘types’ package, the builtins have to be registered as such and as ‘predeclared’ functions:

Source Code 3.2: Registering new built-in functions

```
107 // ...
    // A builtinId is the id of a builtin function.
    type builtinId int
110
    const (
      // universe scope
      _Append builtinId = iota
      _Prepend
115   _Fmap
      _Foldr
      _Foldl
      // ...
```

```
144 // ...
145 var predeclaredFuncs = [...]struct {
      name     string
      nargs    int
      variadic bool
```

```
  kind     exprKind
}{
  _Append:  {"append", 1, true, expression},
  _Prepend: {"prepend", 2, false, expression},
  _Fmap:    {"fmap", 2, false, expression},
  _Foldr:   {"foldr", 3, false, expression},
  _Foldl:   {"foldl", 3, false, expression},
  _Cap:     {"cap", 1, false, expression},
  // ...
```

This registration defines the type of the built-in - they are all expressions, as they return a value - and the number of arguments. After that, the type-checking and its associated tests can be implemented.

This concludes the type-checking for external tools and makes 'gopls' return errors Once type-checking the new built-in functions is implemented, 'gopls' can be compiled against the new public packages.[2] It will then return errors if the wrong types are used. For example, when trying to prepend an integer to a string slice:

```
package main

import "fmt"

func main() {
    fmt.Println(prepend(3, []string{"hello", "world"}))
}
```

Gopls will report a type-checking error:

```
$ gopls check main.go
/tmp/playground/main.go:6:22-23: cannot convert 3 (untyped int constant)
↪  to string
```

[2]This means pointing the go toolchain to the correct directory by setting the value of 'GOROOT' with `go env -w GOROOT=<path>`.

3.1.4 Private packages

In the private packages - the actual compiler - the expressions have to be type-checked, ordered and transformed.

The type-checking process is similar to the one executed for external tools. It should also check the node's child nodes, meaning an operations arguments, body and init statements. Furthermore, during the type-checking process, the built-in function's return types are set and node types may be converted, if possible and necessary. An operation may expect it's arguments to be in `node.Left` and `node.Right`, which means type-checking will also need to move the argument nodes from their default location in `node.List` to `node.Left` and `node.Right`.

Ordering ensures the evaluation order and re-orders expressions. All of the new built-in functions will be evaluated left-to-right and there are now special cases to handle.

Transforming means changing the AST nodes from the built-in operation to nodes that the compiler knows how to translate to SSA. The actual algorithm that these functions use cannot be implemented in normal Go code, they have to be translated directly to AST nodes and statements.

There are more steps to compiling Go code, for example escape-checking, SSA conversion and a lot of optimisations. These are not necessary to implement and do not have a direct relation to the new built-ins, which is why these steps are elided in this paper.

The actual algorithms and part of the implementations for the builtin functions are covered in the following chapters. [3]

fmap

To make the implementation in the AST easier, the algorithm will first be developed in Go, and then translated. Implementing fmap in Go is relatively simple:

Source Code 3.3: Fmap implementation in Go

```
func fmap(fn func(Type) Type1, src []Type) (dest []Type1) {
    for _, elem := range src {
        dest = append(dest, fn(elem))
```

[3] The full implementations can be viewed by diff-ing the git repository between the references 'bachelor-thesis' and 'go1.14'[50].

```
    }
    return dest
}
```

However, there is room for improvement within that function. Instead of calling `append` at every iteration of the loop, the slice can be allocated with `make` at the beginning of the function. Thus, calls to grow the slice at runtime can be saved.

Source Code 3.4: Improved implementation of fmap

```
func fmap(fn func(Type) Type1, src []Type) []Type1 {
    dest := make([]Type1, len(src))
    for i, elem := range src {
        dest[i] = fn(elem)
    }
    return dest
}
```

This algorithm can be translated to the following AST node:

Source Code 3.5: fmap AST translation[51]

```
// ...
// walkfmap rewrites the builtin fmap(f(in) out, []slice) to
//
//   init {
//     dst = make([]out, len(slice))
//     for i, e := range slice {
//       dst[i] = f(e)
//     }
//   }
//   dst
//
func walkfmap(n *Node, init *Nodes) *Node {
  // ...
```

prepend

The general algorithm for 'prepend' is:

Source Code 3.6: prepend implementation in Go

```
func prepend(elem Type, slice []Type) []Type {
    dest := make([]Type, 1, len(src)+1)
    dest[0] = elem
    return append(dest, slice...)
}
```

The call to `make(...)` creates a slice with the length of 1 and the capacity to hold all elements of the source slice, plus one. By allocating the slice with the full length, another slice allocation within the call to `append(...)` is saved. The element to prepend is added as the first element of the slice, and append will then copy the 'src' slice into 'dest'.

The implementation within 'walkprepend' reflects these lines of Go code, but as AST nodes:

Source Code 3.7: prepend AST translation[52]

```
2998 // ...
// walkprepend rewrites the builtin prepend(elem, slice) to
3000 //
//   init {
//     dest := make([]<T>, 1, len(slice)+1)
//     dest[0] = elem
//     append(dest, slice...)
3005 //   }
//   dest
//
func walkprepend(n *Node, init *Nodes) *Node {
  // ...
```

foldr and foldl

As outlined in Chapter 2.1.6, there will be two fold functions; foldr and foldl. foldr behaves exactly like its Haskell counterpart, while foldl behaves like foldl' in Haskell.

While the fold algorithms are most obvious when using recursion, due to performance considerations, an imperative implementation has been chosen:

Source Code 3.8: fold implementation in Go

```
func foldr(fn func(Type, Type1) Type1, acc Type1, slice []Type) Type1 {
    for i := len(s) - 1; i >= 0; i-- {
        acc = fn(s[i], acc)
    }
    return acc
}

func foldl(fn func(Type1, Type) Type1, acc Type1, slice []Type) Type1 {
    for i := 0; i < len(s); i++ {
        acc = f(acc, s[i])
    }
    return acc
}
```

The code further clarifies the differences between the two different folds; the slice is processed in reverse order for foldr (as it would be if this algorithm would have been implemented with recursion), and the order of arguments to the fold function is switched.

The AST walk translates fold to:

Source Code 3.9: fold AST translation[53]

```
// ...
// walkfold rewrites the builtin fold function.
// For the right fold:
//   foldr(f(T1, T2) T2, a T2, s []T1) T2
//
//     init {
//       acc = a
//       for i := len(s) - 1; i >= 0; i-- {
```

```
//          acc = f(s[i], acc)
//        }
//      }
//      acc
//
// And the left fold:
//   foldl(f(T2, T1) T2, a T2, s []T1) T2
//
//      init {
//        acc = a
//        for i := 0; i < len(s); i++ {
//          acc = f(acc, s[i])
//        }
//      }
//      acc
func walkfold(n *Node, init *Nodes, isRight bool) *Node {
  // ...
```

3.2 Functional Check

4 Application

5 Experiments and Results

(Zusammenfassung der Resultate)

6 Discussion

– Bespricht die erzielten Ergebnisse bezüglich ihrer Erwartbarkeit, Aussagekraft und Relevanz
– Interpretation und Validierung der Resultate
– Rückblick auf Aufgabenstellung, erreicht bzw. nicht erreicht
– Legt dar, wie an die Resultate (konkret vom Industriepartner oder weiteren Forschungsarbeiten; allgemein) angeschlossen werden kann; legt dar, welche Chancen die Resultate bieten

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Glossary

AST Abstract Syntax Tree, an abstract representation of source code as a tree. 14

DAG Directed Acyclic Graph. 14

SSA Single Static Assignment, an intermediate representation between the AST and the compiled binary that simplifies and improves compiler optimisations. 15

Appendices

1 Analysis of function occurrences in Haskell code

The results of the analysis have been aquired by running the following command from the root of the git repository[54]:

```
./work/common-list-functions/count-function.sh "map " " : " "fold"
↪  "filter " "reverse " "take " "drop " "maximum" "sum " "zip "
↪  "product " "minimum " "reduce "
```

2 Workaround for the missing foldl' implementation in Go

Source Code 1: Working around the missing foldl implementation in Go

```
package main

import "fmt"

func main() {
        zero, one, two, three := 0, 1, 2, 3
        list := []*int{&one, &two, nil, &three, &zero}

        // this will work, as the values will be evaluated
        // "lazily" - the nested functions will never
        // be executed, thus it will never panic.
        fmt.Printf("%v\n", myFold(mulLazy, 1, list))
        // This will panic.
        fmt.Printf("%v\n", foldl(mul, 1, list))
}

func mul(x int, y *int) int {
        if *y == 0 {
                return 0
        }
        return x * *y
}

func mulLazy(x func() int, y *int) func() int {
        return func() int {
```

```
                if *y == 0 {
                        return 0
                }
                return x() * *y
        }
}

func myFold(f func(func() int, *int) func() int, acc int, list []*int)
↪  int {
        a := func() int { return acc }
        a = foldl(f, a, list)
        return a()
}
```

```
$> fgo run .
0
panic: runtime error: invalid memory address or nil pointer dereference
[signal SIGSEGV: segmentation violation code=0x1 addr=0x0 pc=0x109e945]

goroutine 1 [running]:
main.what(0x2, 0x0, 0x2)
        /tmp/map/main.go:16 +0x5
main.main()
        /tmp/map/main.go:12 +0x187
exit status 2
```

Anhang/Appendix:
- Projektmanagement:
  - Offizielle Aufgabenstellung, Projektauftrag
  - (Zeitplan)
  - (Besprechungsprotokolle oder Journals)
- Weiteres:
  - CD/USB-Stick mit dem vollständigen Bericht als PDF-File inklusive Film- und Fotomaterial
  - (Schaltpläne und Ablaufschemata)
  - (Spezifikation u. Datenblätter der verwendeten Messgeräte und/oder Komponenten)
  - (Berechnungen, Messwerte, Simulationsresultate)
  - (Stoffdaten)
  - (Fehlerrechnungen mit Messunsicherheiten)
  - (Grafische Darstellungen, Fotos)
  - (Datenträger mit weiteren Daten (z. B. Software-Komponenten) inkl. Verzeichnis der auf diesem Datenträger abgelegten Dateien)
  - (Softwarecode)