A trait system for the uniform expression of run-time and compile-time polymorphism in Fortran

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Abstract

Based on conclusions drawn from a survey of modern languages, a trait system for Fortran is developed and described that is fully backwards compatible with the present Fortran language, and allows for the uniform management of source code dependencies on both user-defined and language-intrinsic types, via run-time and compile-time polymorphism (i.e. "object-oriented" and "generic" programming). The feature set described here is small enough to facilitate a first prototype implementation in an open source compiler, like LFortran, but at the same time comprehensive enough to already endow Fortran with polymorphism capabilities that largely equal those of modern programming languages like Swift, Rust, or Go. The discussed new features are expected to transform the way Fortran applications and libraries will be written in the future. Decoupled software plugin architectures with enormously improved source code flexibility, reusability, maintainability, and reliability will become possible, without any need for run-time type inspections, and without any loss in computational performance.

Chapter 1

Introduction

Polymorphism was discovered in the 1960s by Kristen Nygaard and Ole-Johan Dahl during their development of Simula 67, the world's first object-oriented (OO) language [3]. Their work introduced into programming what is nowadays known as "virtual method table" (i.e. function-pointer) based run-time polymorphism, which is both the first focus of this document, and the defining feature of all OO languages. Several other forms of polymorphism are known today, the most important of them being parametric polymorphism [1] (also known as "generics"), which is the second focus of this document, and which has historically developed disjointly from run-time polymorphism, since it makes use of compile-time mechanisms.

1.1 The purpose of polymorphism

But what is the purpose of polymorphism in a programming language? What is polymorphism actually good for? One of the more comprehensive answers to this question was given by Robert C. Martin in numerous books (e.g. [11]), as well as in the following quotation from his blog [10]:

> "There really is only one benefit to polymorphism; but it's a big one. It is the inversion of source code and run time dependencies. In most software systems when one function calls another, the runtime dependency and the source code dependency point in the same direction. The calling module depends on the called module. However, when polymorphism is injected between the two there is an inversion of the source code dependency. The calling module still depends on the called module at run time. However, the source code of the calling module does not depend upon the source code of the called module. Rather both modules depend upon a polymorphic interface. This inversion allows the called module to act like a plugin. Indeed, this is how all plugins work."

Notice, the absence of the words "code reuse" in these statements. The purpose of polymorphism, according to Martin, is the "inversion" (i.e. replacement, or management) of source code dependencies by (means of) particular abstractions, i.e. polymorphic interfaces (or protocols/-traits, as they are also known today). The possibility to reuse code is then merely the logical consequence of such proper dependency management.

1.2 Source code dependencies in statically typed languages

Which then are the source code dependencies that polymorphism helps us manage? It has been customary to make the following distinction when answering this question:

- Firstly, most larger programs that are written in statically typed languages (like Fortran) have dependencies on *user-defined* procedures and data types. If the programmer employs encapsulation of both a program's procedures and its data, i.e. its state, both these dependencies can actually be viewed as dependencies on user-defined abstract data types. That is, types that contain both user-defined state, and implementation code which operates on that (hidden) state. These are the dependencies that Martin is concretely referring to in the above quotation, and it is these dependencies on (volatile) implementation (details) that are particularly troublesome, because they lead to rigid coupling between the various different *parts* of an application. Their results are recompilation cascades, the non-reusability of higher-level modules, the impossibility to comprehend a large application incrementally, and fragility of such an application as a whole.

- Secondly, every program, that is written in a statically typed language, also has dependencies on abstract data types that are provided by the language itself. Fortran's `integer`, `real`, etc. intrinsic types are examples of language intrinsic abstract data types. While hard-wired dependencies on such intrinsic types may not couple different parts of a program (because the implementations of these types are supplied by the language), they nevertheless make a program's source code rigid with respect to the data that it can be used on.

The most widely used approaches to manage dependencies on language intrinsic types have so far been through generics, while dependency management of user-defined (abstract data) types has so far been the task of OO programming and OO design patterns. Martin [11] has, for instance, defined object-orientation as follows:

> "OO is the ability, through the use of polymorphism, to gain absolute control over every source code dependency in [a software] system. It allows the architect to create a plugin architecture, in which modules that contain high-level policies are independent of modules that contain low-level details. The low-level details are relegated to plugin modules that can be deployed and developed independently from the modules that contain high-level policies."

1.3 Modern developments

Notice how Martin's modern definition of object-orientation, that emphasizes source code decoupling, is the antithesis to the usually taught "OO" approaches of one class rigidly inheriting implementation code from another. Notice also how his definition does not require some specific type of polymorphism for the task of dependency management, as long as (according to Martin's first quotation) the mechanism is based on polymorphic interfaces.

Martin's statements on the purpose of both polymorphism and OO simply reflect the two crucial developments that have taken place in these fields over the last decades. Namely, the realizations that

- run-time polymorphism should be freed from the conflicting concept of implementation inheritance (to which it was originally bound given its Simula 67 heritage), and be formulated

exclusively in terms of conformance to polymorphic interfaces, i.e. function signatures, or purely procedural abstractions, and that

- compile-time polymorphism should be formulated in exactly the same way as well.

These two developments taken together have recently opened up the possibility to treat polymorphism, and hence the dependency management of both user-defined and language intrinsic types, uniformly in a programming language. As a consequence, it has become possible to use the potentially more efficient (but also less flexible) mechanism of compile-time polymorphism also for a number of tasks that have traditionally been reserved for run-time polymorphism (i.e. OO programming), and to mix and match the two polymorphism types inside a single application to better satisfy a user's needs for both flexibility and efficiency.

1.4 Historical background

The road towards these realizations has been surprisingly long. Over the last five decades, a huge body of OO programming experience first had to demonstrate that the use of (both single and multiple) implementation inheritance breaks encapsulation in OO languages, and therefore results in extremely tightly coupled, rigid, fragile, and non-reusable code. This led to an entire specialized literature on OO design patterns [4, 9, 6], that aimed at avoiding or mitigating the effects of such rigidity, by replacing the use of implementation inheritance with the means to formulate run-time polymorphism that are discussed below. It also led to the apprehension that implementation inheritance (but *not* run-time polymorphism) should be abandoned [13]. In modern languages, implementation inheritance is either kept solely for backwards compatibility reasons (e.g. in the Swift and Carbon languages), or it is foregone altogether (e.g. in Rust, and Go).

The first statically typed mainstream programming language that offered a proper separation of run-time polymorphism from implementation inheritance was Objective C. It introduced "protocols" (i.e. polymorphic interfaces) in the year 1990 [2]. Protocols in Objective C consist of pure function signatures, that lack implementation code. Objective C provided a mechanism to implement multiple such protocols by a class, and to thus make classes conform to protocols. This can be viewed as a restricted form of multiple inheritance, namely inheritance of object *specification*, which is also known as *subtyping*. Only a few years later, in 1995, the Java language hugely popularized these ideas using the terms "interfaces" and "interface inheritance" [2]. Today, nearly all modern languages support polymorphic interfaces/protocols, and the basic mechanism of multiple interface inheritance that was introduced to express run-time polymorphism in Objective C, often in even improved, more flexible, manifestations. The only negative exceptions in this respect being modern Fortran, and C++, which both still stick to the obsolescent Simula 67 paradigm.

A similar learning process, as that outlined for run-time polymorphism, took place in the field of compile-time/parametric polymorphism. Early attempts, notably templates in C++, to render function arguments and class parameters polymorphic, did not impose any constraints on such arguments and parameters, that could be checked by C++ compilers. With the known results on compilation times and cryptic compiler error messages [5]. Surprisingly, Java, the language that truly popularized polymorphic interfaces in OO programming, did not provide an interface based mechanism to constrain its generics. Within the pool of mainstream programming languages, this latter realization was first made with the advent of Rust [12].

Rust came with a trait (i.e. polymorphic interface) system with which it is possible for the user to uniformly and transparently express both generics (i.e. compile-time) and run-time polymorphism in the same application, and to relatively easily switch between the two, where possible.

Rust's traits are an improved form of protocols/interfaces in that the user can implement them for a type without having these implementations be coupled to the type's actual definition. Thus, existing types can be made to retroactively implement new traits, and hence be used in new settings (with some minor restrictions on user ownership of either the traits or the types).

Rust's main idea was quickly absorbed by almost all other mainstream modern languages, most notably Go, Swift, and Carbon, with the difference that these latter languages tend to leave the choice between static and dynamic procedure dispatch to the compiler, or language implementation, rather than the programmer. C++ is in the process of adopting generics constraints for its "templates" under the term "strong concepts", but without implementing the greater idea to uniformly express *all* the polymorphism in the language through them. An implementation of this latter idea must today be viewed as a prerequisite in order to call a language design "modern". The purpose of this document is to describe additions to Fortran, that aim to provide the Fortran language with such modern capabilities.

Chapter 2

Case Study: Calculating the average value of a numeric array

To illustrate the advanced features and capabilities of some of the available modern programming languages with respect to polymorphism, and hence dependency management, we will make use here of a case study: the simple test case of calculating the average value of a set of numbers stored inside a one-dimensional array. In the remainder of this chapter we will first provide an account and some straightforward monomorphic (i.e. coupled) functional implementation of this test problem, followed by a functional implementation that makes use of both run-time and compile-time polymorphism to manage source code dependencies. In the survey of programming languages presented in Chapter 3, we will then recode this test problem in an encapsulated fashion, to highlight how the source code dependencies in this problem can be managed in different languages even in more complex situations, that require OO techniques.

2.1 Monomorphic functional implementation

We have chosen Go here as a language to illustrate the basic ideas. Go is easily understood, even by beginners, and is therefore well suited for this purpose (another good choice would have been the Swift language). The code in the following Listing 2.1 should be self explanatory for anyone who is even only remotely familiar with the syntax of C family languages. So, we'll make only a few remarks regarding syntax.

- While mostly following a C like syntax, variable declarations in Go are essentially imitating Pascal syntax, where a variable's name precedes the declaration of the type.
- Go has two assignment operators. The usual = operator, as it is known from other languages, and the separate operator `:=` that is used for combined declaration and initialization of a variable.
- Go has array slices that most closely resemble those of Python's Numpy (which exclude the upper bound of an array slice).

Our basic algorithm for calculating the average value of an array of integer elements employs two different implementations for averaging. The first makes use of a "simple" summation of all the array's elements, in ascending order of their array index. While the second sums in a "pairwise" manner, dividing the array in half to carry out the summations recursively, and switching to the "simple" method once subdivision is no longer possible.

As a result, this code has three levels of hard-wired (i.e. rigid) dependencies. Namely,

1. function `pairwise_sum` depending on function `simple_sum`'s implementation,
2. functions `simple_average` and `pairwise_average` depending on functions' `simple_sum`, and `pairwise_sum` implementation, respectively, and
3. the entire program depending rigidly on the `int32` data type in order to declare both the arrays that it is operating on, and the results of its summation and averaging operations.

The first two items are dependencies on user-defined implementations, while the third is a typical case of rigid dependency on a language intrinsic type, which renders the present code incapable of being applied to arrays of any other data type than `int32`s. Given that we are dealing with three levels of dependencies, three levels of polymorphism will accordingly be required to remove all these dependencies.

Listing 2.1: Monomorphic functional version of the array averaging example in Go.

```go
package main

import "fmt"

func simple_sum(x []int32) int32 {
   var s int32
   s = 0
   for i := 0; i < len(x); i++ {
     s += x[i]
   }
   return s
}

func pairwise_sum(x []int32) int32 {
   if len(x) <= 2 {
      return simple_sum(x)
   } else {
      m := len(x) / 2
      return pairwise_sum(x[:m+1]) + pairwise_sum(x[m+1:])
   }
}

func simple_average(x []int32) int32 {
   return simple_sum(x) / int32(len(x))
}

func pairwise_average(x []int32) int32 {
   return pairwise_sum(x) / int32(len(x))
}

// ..............
// main program
```

```
// ..............

func main() {

   xi := []int32{1,2,3,4,5}

   var key int32

   fmt.Println("Simple    sum average: 1")
   fmt.Println("Pairwise sum average: 2")
   fmt.Print("Choose an averaging method: ")
   fmt.Scan(&key)

   switch key {
   case 1:
      fmt.Println(simple_average(xi))
   case 2:
      fmt.Println(pairwise_average(xi))
   default:
      fmt.Println("Case not implemented!")
   }

}
```

2.2 Polymorphic functional implementation

Listing 2.2 gives an implementation of our test problem, that employs Go's generics and functional features in order to eliminate the last two of the rigid dependencies that were listed in Sect. 2.1 (we thank Robert Griesemer of the Go team for providing the original code of this particular version of the example). The code makes use of Go's generics to admit arrays of both the `int32` and `float64` types as arguments to all functions, and to express the return values of the latter. It also makes use of the run-time polymorphism inherent in Go's functional features, namely closures and variables of higher-order functions, to replace the two previous versions of function `average` (that depended on specific implementations), by a single polymorphic version. Only the rigid dependency of function `pairwise_sum` on function `simple_sum` has not been removed, in order to keep the code more readable. In the OO code versions, that will be presented in Chapter 3, even this dependency is eliminated.

A few remarks are in order for a better understanding of Listing 2.2's code:

- In Go, generic type parameters to a function, like the parameter `T` here, are provided in a separate parameter list, that is enclosed in brackets [ ].
- Generic type parameters have a constraint that follows their declared name. Go exclusively uses interfaces as such constraints (see the interface `INumeric` in the present example).
- Interfaces consist of either function signatures, or *type sets*, like "`int32 | float64`" in the present example. The latter signify a set of function signatures, too, namely the signatures of

the intersecting set of all the operations/functions for which the listed types provide implementations.

- The code makes use of type conversions to the generic type `T`, where required. For instance, `T(0)` converts the constant `0` to the corresponding zero constant of type `T`.
- The code instantiates closures and stores these by value in two variables named `avi` and `avf` for later use (Fortran and C programmers should note that `avi` and `avf` are *not* function pointers!).

Listing 2.2: Polymorphic functional version of the array averaging example in Go.

```
package main

import "fmt"

type INumeric interface{ int32 | float64 }

func simple_sum[T INumeric](x []T) T {
   var s T
   s = T(0)
   for i := 0; i < len(x); i++ {
     s += x[i]
   }
   return s
}

func pairwise_sum[T INumeric](x []T) T {
   if len(x) <= 2 {
      return simple_sum(x)
   }
   m := len(x) / 2
   return pairwise_sum(x[:m+1]) + pairwise_sum(x[m+1:])
}

func average[T INumeric](sum func([]T) T, x []T) T {
   return sum(x) / T(len(x))
}

func main() {
   xi := []int32{1, 2, 3, 4, 5}
   xf := []float64{1, 2, 3, 4, 5}

   var key int32
   var avi func([]int32) int32
   var avf func([]float64) float64

   fmt.Println("Simple   sum average:", 1)
   fmt.Println("Pairwise sum average:", 2)
```

```
38    fmt.Print("Choose an averaging method: ")
39    fmt.Scan(&key)
40
41    switch key {
42       case 1:
43          avi = func(x []int32) int32 {
44                   return average(simple_sum[int32], x)
45                }
46          avf = func(x []float64) float64 {
47                   return average(simple_sum[float64], x)
48                }
49       case 2:
50          avi = func(x []int32) int32 {
51                   return average(pairwise_sum[int32], x)
52                }
53          avf = func(x []float64) float64 {
54                   return average(pairwise_sum[float64], x)
55                }
56       default:
57          fmt.Println("Case not implemented!")
58     }
59
60     fmt.Println(avi(xi))
61     fmt.Println(avf(xf))
62 }
```

The motivation to code the example as in Listing 2.2 is that once the two closures `avi`, and `avf`, are properly instantiated (by means of the `switch` statement), they may be passed from the main program to any other client code that may need to make use of the particular averaging algorithm that was selected by the user. This latter client code would *not* have to be littered with `switch` statements itself, and it would *not* have to depend on any specific implementations. It would merely depend on the closures' interfaces. The same holds for the OO code versions that are discussed in the next chapter, with objects replacing the closures (both being merely slightly different realizations of the same idea).

Chapter 3

Survey of modern languages

In the present chapter we give implementations, in various modern languages, of encapsulated (i.e. OO) code versions of the test problem. As in the functional code version presented in Sect. 2.2, we employ run-time polymorphism to manage the dependencies on user-defined implementations (in this case abstract data types), and generics in order to manage the dependencies on language intrinsic types. This serves to illustrate how both run-time and compile-time polymorphism can be typically used for dependency management in an OO setting in these modern languages. The survey also aims to highlight the many commonalities but also some of the minor differences in the approaches to polymorphism that were taken in these different languages. As a final disclaimer, we do not advocate to code problems in an OO manner that can be easily coded in these languages in a functional way (as it is the case for this problem). However, in more complex cases, where many more nested functions would need to be used, and where state would have to be hidden, the OO programming style would be the more appropriate one. Hence our test problem will stand in, in this chapter, for emulating also such a more complex problem, that would benefit from an encapsulated coding style.

3.1 Go

Go has supported run-time polymorphism through (polymorphic) "interfaces" (and hence modern-day OO programming) since its inception. In Go, encapsulation is done by storing state in a "`struct`" and by binding procedures, that need to use that state, to this same `struct`. Thus creating a user-defined abstract data type (or ADT) with methods. Go allows the programmer to implement multiple polymorphic interfaces for such a type (i.e. to use multiple interface inheritance), even though it offers no explicit language statement for this purpose.

Instead, a user-defined type is implicitly assumed to implement an interface whenever it provides implementations of all the interface's function signatures. This way of implementing interfaces requires only an object reference of the type to be passed to its methods (by means of a separate parameter list, in front of a method's actual name). It is otherwise decoupled from the type's (i.e. the ADT's `struct`) definition. Limitations in Go are that language intrinsic types cannot have methods, and that methods and interfaces cannot be directly implemented for user-defined types whose definitions are located in other packages. That is, the programmer has to write wrappers in the latter case. Go, finally, makes it explicit in its type definition syntax that interfaces (like `structs`) are types in their own right, and that hence polymorphic variables (i.e. objects) can be declared in terms of them.

Since version 1.18, Go also supports compile-time polymorphism through generics. Go's gener-

ics make use of "strong concepts", since they are bounded by constraints that are expressed through interfaces. Hence, the Go compiler will fully type-check generic code. In Go, structures, interfaces, and functions, but not methods, can all be given their own generic type parameters.

3.1.1 Encapsulated version coded in Go

Listing 3.1 gives an encapsulated version of the test problem coded in Go. The two different implementations of the `sum` function have been encapsulated in two different ADTs named `SimpleSum` and `PairwiseSum`, whereas a third ADT named `Averager` encapsulates the functionality that is required to perform the actual averaging. The latter two ADTs contain the lower-level objects "`other`" and "`drv`" of `ISum[T]` type as components, to which they delegate calls to these objects' `sum` methods. Notice how the use of the polymorphic interface `ISum[T]` in the declarations of `other` and `drv` enables either `SimpleSum` or `PairwiseSum` objects to be plugged into their higher-level clients.

A second interface, named `IAverager`, is used to enable polymorphism for different averaging algorithms. Finally, there's a third interface, `INumeric`, that serves exactly the same purpose as in the functional polymorphic version given in Sect. 2.2, namely to make all function arguments and return values polymorphic, by admitting as input and output parameters both the `int32` and `float64` intrinsic types.

Hence, three polymorphic interfaces were required in this code, in order to eliminate the three levels of rigid dependencies that were listed in Sect. 2.1. Notice also that, exempting `INumeric`, all the interfaces and all the user-defined ADTs need to take in generic type parameters in this example. This is required in order to enable all the `sum` and `average` methods to use generic type parameters in Go.

Listing 3.1: Encapsulated Go version of the array averaging example.

```
1  package main
2
3  import "fmt"
4
5  // ...........
6  // Interfaces
7  // ...........
8
9  type INumeric interface {
10    int32 | float64
11 }
12
13 type ISum[T INumeric] interface {
14    sum(x []T) T
15 }
16
17 type IAverager[T INumeric] interface {
18    average(x []T) T
19 }
20
21 // ..............
22 // SimpleSum ADT
23 // ..............
```

```
24
25 type SimpleSum[T INumeric] struct {
26 }
27
28 func (self SimpleSum[T]) sum(x []T) T {
29    var s T
30    s = T(0)
31    for i := 0; i < len(x); i++ {
32      s += x[i]
33    }
34    return s
35 }
36
37 // ................
38 // PairwiseSum ADT
39 // ................
40
41 type PairwiseSum[T INumeric] struct {
42    other ISum[T]
43 }
44
45 func (self PairwiseSum[T]) sum(x []T) T {
46    if len(x) <= 2 {
47       return self.other.sum(x)
48    } else {
49       m := len(x) / 2
50       return self.sum(x[:m+1]) + self.sum(x[m+1:])
51    }
52 }
53
54 // ............
55 // Averager ADT
56 // ............
57
58 type Averager[T INumeric] struct {
59    drv ISum[T]
60 }
61
62 func (self Averager[T]) average(x []T) T {
63    return self.drv.sum(x) / T(len(x))
64 }
65
66 // ............
67 // main program
68 // ............
69
70 func main() {
71
```

```
72      var avi IAverager[int32]
73      var avf IAverager[float64]
74
75      xi := []int32{1,2,3,4,5}
76      xf := []float64{1.,2.,3.,4.,5.}
77
78      var key int32
79
80      fmt.Println("Simple␣␣␣sum␣average:␣1")
81      fmt.Println("Pairwise␣sum␣average:␣2")
82      fmt.Print("Choose␣an␣averaging␣method:␣")
83      fmt.Scan(&key)
84
85      switch key {
86      case 1:
87         avi = Averager[int32]{ SimpleSum[int32]{} }
88         avf = Averager[float64]{ SimpleSum[float64]{} }
89      case 2:
90         avi = Averager[int32]{ PairwiseSum[int32]{ SimpleSum[int32]{} } }
91         avf = Averager[float64]{ PairwiseSum[float64]{ SimpleSum[float64]{} } }
92      default:
93         fmt.Println("Case␣not␣implemented!")
94      }
95
96      fmt.Println(avi.average(xi))
97      fmt.Println(avf.average(xf))
98  }
```

The main program makes use of Go's built-in structure constructors, and constructor chaining, in order to instantiate objects of the required ADTs. In particular, it instantiates run-time polymorphic "`Averager`" objects (depending on whether simple or pairwise sum averaging is to take place), and it does so for both the `int32` and `float64` types separately, in order to then use these objects on `int32` and `float64` data, respectively. The fact that `two` such objects are required (one for each language intrinsic data type) is connected to the fact that in order to obtain generic methods in Go, one has to parameterize interfaces by generic parameters, and instantiate them with different actual data types, as in `func main`'s first two code lines. A single (i.e. unparameterized) `IAverager` interface therefore doesn't suffice, which is unfortunate from the user's perspective, as some code duplication in client code cannot be avoided in this way.

3.2 Rust

Like Go, Rust supports both run-time and compile-time polymorphism through polymorphic interfaces, which Rust calls "traits". In contrast to Go, Rust has its programmers implement traits in an explicit manner, by using explicit "`impl`" code blocks to provide a trait's method implementations. These same `impl` blocks also serve to bind methods to a type that aren't a part of some trait, like e.g. user-defined constructors for `structs` (see the functions named "`new`" in the following code Listing 3.2).

Differing from Go, Rust allows the programmer to implement traits for both user-defined *and*

language intrinsic types, and to do so for types that are located in external libraries (called "crates" in Rust), as long as the traits themselves are defined in the programmer's own crate. The reverse, namely implementing an external trait for a user-owned type, is also possible. Only the (edge) case of implementing an external trait for an external type is not allowed (this is called the "orphan rule" [7]). The latter case requires the use of wrappers.

Comparable to Go, Rust's generics model allows for the generic parameterization of functions, traits, and user-defined types like `structs`. Rust does not explicitly forbid generic methods. However, if one defines such a method within a trait, then this will make the trait unusable for the declaration of any "trait objects" [8], i.e. for the employment of run-time polymorphism. Thus, the Rust programmer will in general (need to) parameterize traits and `structs` rather than any methods themselves. Rust generics are fully type-checked at compilation time, i.e. Rust supports "strong concepts".

3.2.1 Encapsulated version coded in Rust

The encapsulated Rust version of our test problem that is given in the following Listing 3.2 is in its outline quite similar to the corresponding Go version. There are, however, a few minor differences, that are listed in the following notes.

- Rust uses angled brackets to indicate generic parameter lists.
- Generics constraints in Rust are typically enforced by specifying the required traits in `impl` blocks using `where` statements.
- Use of a "`Num`" trait from the external "`num`" crate was necessary, in order to enable numeric operations on generic types, which leads to dependency on external library code.
- At times, use of the "`Copy`" trait also had to be made, to work around Rust's default move semantics.
- In order to help make all of the source code dependencies explicit, our Rust version employs modules, and `use` statements to import the required functionality.
- Despite reliance on external dependencies, conversion to generic types wasn't possible. This led to the necessity to move the type conversion from method `average` to its calls in the main program. We also had to import a `zero` generic function from the external `num` crate, in order to initialize the variable `s` that is returned by the `sum` method of the `SimpleSum` ADT.
- Rust's default structure constructors suffer from the same flaw as Fortran's. That is, they are unable to initialize from an external scope, structure components that are declared being private to their module. As in Fortran, use of user-defined constructors must be made instead (see the functions named `new` that are defined in separate `impl` blocks for the ADTs `PairwiseSum` and `Averager`).
- To declare run-time polymorphic variables one has to put so-called "trait objects" into "Boxes", i.e. to declare smart pointers of them, for dynamic instantiation and memory allocation (this is the Rust equivalent to using `allocatable` polymorphic objects in Fortran).

Listing 3.2: Encapsulated Rust version of the array averaging example.

```rust
pub mod interfaces {

    // ...........
    // Interfaces
    // ...........

    pub trait ISum<T> {
        fn sum(&self, x: &[T]) -> T;
    }

    pub trait IAverager<T> {
        fn average(&self, x: &[T], length: T) -> T;
    }
}

pub mod simple_library {

    use num::{zero,Num};
    use crate::interfaces::{ISum};

    // ..............
    // SimpleSum ADT
    // ..............

    pub struct SimpleSum {
    }

    impl<T> ISum<T> for SimpleSum where T: Num + Copy {
        fn sum(&self, x: &[T]) -> T {
            let mut s: T = zero();
            for i in 0 .. x.len() {
                s = s + x[i];
            }
            return s
        }
    }

}

pub mod pairwise_library {

    use num::{Num};
    use crate::interfaces::{ISum};

    // .................
    // PairwiseSum ADT
```

```
    // ..............

    pub struct PairwiseSum<T> {
        other: Box<dyn ISum<T>>,
    }

    impl<T> PairwiseSum<T> where T: Num {
        pub fn new(other: Box<dyn ISum<T>>) -> PairwiseSum<T> {
            PairwiseSum{
                other: other,
            }
        }
    }

    impl<T> ISum<T> for PairwiseSum<T> where T: Num {
        fn sum(&self, x: &[T]) -> T {
            let n = 2;
            let l = x.len();
            if  l <= n {
                return self.other.sum(x);
            } else {
                let m = x.len() / 2;
                return self.sum(&x[0..m+1]) + self.sum(&x[m+1..l]);
            }
        }
    }

}

pub mod averager_library {

    use num::{Num};
    use crate::interfaces::{ISum,IAverager};

    // ............
    // Averager ADT
    // ............

    pub struct Averager <T> {
        drv: Box<dyn ISum<T>>,
    }

    impl<T> Averager<T> where T: Num {
        pub fn new(drv: Box<dyn ISum<T>>) -> Averager<T> {
            Averager{
                drv: drv,
            }
        }
```

```
    }

    impl<T> IAverager<T> for Averager<T> where T: Num {
        fn average(&self, x: &[T], length: T) -> T {
            return self.drv.sum(&x) / length;
        }
    }

}

// ..............
// main program
// ..............

#[macro_use] extern crate text_io;

fn main() {
    use crate::interfaces::{IAverager};
    use crate::simple_library::{SimpleSum};
    use crate::pairwise_library::{PairwiseSum};
    use crate::averager_library::{Averager};

    let avsi = Averager::new( Box::new( SimpleSum{} ));
    let avsf = Averager::new( Box::new( SimpleSum{} ));

    let avpi = Averager::new(Box::new(PairwiseSum::new(Box::new(SimpleSum{}))));
    let avpf = Averager::new(Box::new(PairwiseSum::new(Box::new(SimpleSum{}))));

    let mut avi: Box<dyn IAverager::<i32>> = Box::new(avsi);
    let mut avf: Box<dyn IAverager::<f64>> = Box::new(avsf);

    let xi : [i32;5] = [1,2,3,4,5];
    let xf : [f64;5] = [1.,2.,3.,4.,5.];

    let key: i32;

    println!("Simple   sum average: 1");
    println!("Pairwise sum average: 2");
    scan!("{}\n",key);

    match key {
        1 => {}
        2 => { avi = Box::new(avpi);
               avf = Box::new(avpf);
        }
        _ => { println!("Case not implemented!");
        }
    }
```

```
143
144     println!("{}", avi.average(&xi, xi.len() as i32));
145     println!("{}", avf.average(&xf, xf.len() as f64));
146 }
```

The main program in the Rust version is somewhat longer then in the corresponding Go version because of the need to import dependencies from modules (as it would be necessary in realistic situations). Its logic is also somewhat convoluted compared to the Go version, because Rust doesn't allow the programmer to declare variables that aren't initialized upon declaration, and because of the aforementioned necessity to move the required type conversions out of method `average`, and into the calls of this method. Otherwise the codes are pretty much identical.

3.3 Swift

Being a successor language to Objective C, Swift differs slightly from the languages considered so far in that it opted to retain implementation inheritance for backwards compatibility to Objective C, whereas both Go and Rust do not support implementation inheritance *by design*. Swift therefore supports "classical" classes, but it also allows one to bind methods to structures (which, in contrast to classes, are value types in Swift).

Like Go and Rust, Swift (furthermore) supports a trait system in order to implement both runtime and compile-time polymorphism through polymorphic interfaces, that are called "protocols" in Swift. If the Swift programmer chooses to ignore implementation inheritance and classes, he can therefore very much program with structures and protocols in Swift as he would with structures and interfaces/traits in Go and Rust, respectively.

Given Swift's backwards compatible design, implementation of a protocol (i.e. interface inheritance) is usually done as in "classical" OO languages, i.e. within a structure's or a class's definition. The ":" operator followed by one or more interface names must be supplied for this purpose after the structure's or class's own name. However, a very powerful facility for types to implement protocols retroactively is also provided, through so-called "`extensions`", that work even if the types' source code is inaccessible (because one is, e.g., working with a library in binary form). This same facility also allows the implementation of protocols for language-intrinsic types. For instance, the following little program prints out "`I am 4.9`":

```
1  protocol IPrinter {
2      func out()
3  }
4  extension Float64: IPrinter {
5      func out() {
6          print("I␣am␣\(self)")
7      }
8  }
9  var x: Float64 = 4.9
10 x.out()
```

Swift generics support "strong concepts", and are thus fully type-checked at compile time, and their capabilities are on par with those of Go and Rust. In one aspect they are even superior, namely in that Swift allows for parameterized *methods*, instead of parameterized protocols. This has some interesting, positive implications for the Swift programmer, that will be discussed in detail below.

3.3.1 Encapsulated version coded in Swift

Listing 3.3 gives an example of how the encapsulated version of the array averaging test problem can be programmed in Swift. See the following remarks in order to understand this code:

- Swift uses angled brackets <> to indicate generic parameter lists.
- Type constraints are formulated by supplying a protocol name after a type parameter (separated by a colon).
- Swift does not supply an equivalent to Go's `int32 | float64` syntax. Hence the user must use a `Numeric` protocol defined by the standard library, as a constraint for numeric types. Which leads to reliance on library code.
- Unfortunately, Swift's `Numeric` protocol does *not* support the division operation! Hence the division that would have been required in function `average` of the `Averager` ADT had to be moved out to the calling code of the main program.
- The Swift version makes use of language built-in, default, structure constructors (called "initializers").
- Array slices are not arrays themselves. So an explicit conversion using an `Array()` constructor is required in such cases.
- By default, function and method calls in Swift make use of keyword arguments.
- The syntax for type conversion into a generic type `T` is somewhat peculiar. E.g. Go's `T(0)` is written as `T(exactly:0)!` in Swift (making use of the mandatory keyword "`exactly`" in the function responsible for the type conversion).

Listing 3.3: Encapsulated Swift version of the array averaging example.

```
// ...........
// Interfaces
// ...........

protocol ISum {
    func sum<T: Numeric>(x: [T]) -> T
}

protocol IAverager {
    func average<T: Numeric>(x: [T]) -> T
}

// ..............
// SimpleSum ADT
// ..............

struct SimpleSum: ISum {

    func sum<T: Numeric>(x: [T]) -> T {
```

```
        var s: T
        s = T(exactly:0)!
        for i in 0 ... x.count-1 {
            s += x[i]
        }
        return s
    }
}

// ..............
// PairwiseSum ADT
// ..............

struct PairwiseSum: ISum {
    var other: ISum

    func sum<T: Numeric>(x: [T]) -> T {
        if ( x.count <= 2 ) {
            return other.sum(x: x)
        } else {
            let m = x.count / 2
            return sum(x: Array(x[..<m])) + sum(x: Array(x[m...]))
        }
    }

}

// ............
// Averager ADT
// ............

struct Averager: IAverager {
    var drv: ISum

    func average<T: Numeric>(x: [T]) -> T {
        return drv.sum(x: x)
    }
}

// ............
// main program
// ............

let avs = Averager(drv: SimpleSum())
let avp = Averager(drv: PairwiseSum(other: SimpleSum()))

var av : IAverager = avs

```

```
var xi: [Int32] = [1,2,3,4,5]
var xf: [Float64] = [1.0,2.0,3.0,4.0,5.0]

var key: Int32?

print("Simple   sum average: 1")
print("Pairwise sum average: 2")
print("Choose an averaging method: ")
key = Int32(readLine()!)

switch key {
case 1:
    // simple sum case
    av = avs
case 2:
    // pairwise sum case
    av = avp
default:
    print("Case not implemented!")
}

print( av.average(x: xi) / Int32(xi.count) )
print( av.average(x: xf) / Float64(xf.count) )
```

Even a casual glance at the Swift version will show that the Swift code is the easiest to read and understand among all the encapsulated implementations. This is largely the result of Swift supporting generic methods, and hence not requiring the programmer to parameterize and instantiate any generic interfaces/protocols, in contrast to both Go and Rust. The consequences are

- that method genericity for an ADT's objects can be expressed using only a single, as opposed to multiple protocols,
- that merely a *single* object instance of that same protocol is required, in order to be able to operate on many different language intrinsic data types, and
- that this also largely *obviates the need for manual instantiations of generics in Swift* (because generic functions/methods are easier to instantiate automatically by the compiler, as it can always infer the required types by checking the actual arguments that are passed to a function/method)!

As an example, consider the `IAverager` protocol in the above Swift code. There's only a single (i.e. unparameterized) version of this protocol. Consequently, there's only a need in the main program to declare a single object variable, `av`, of that protocol (that enables `av` to be polymorphically assigned different `structs` that implement `IAverager`). Because it contains an "`average`" method that is generic, this *single* object can then be straightforwardly used on data of *both* the `Int32` and `Float64` types!

This vastly simplifies client code that needs to make use of objects such as `av`, especially if such client code needs to work on *many* more types than just `Int32` and `Float64`. Contrast this with Go's and Rust's model, where manual instantiation of a different version of `IAverager` is required for *every* different generic type parameter that the user wishes to employ. Notice also, how there's

not a single manual instantiation of generics code required in the Swift example! We consider these significant advantages of the generics approach that is taken in Swift vs. that of Go and Rust.

3.4 Conclusions

The use of run-time polymorphism by means of interfaces is rather similar in all the languages considered here. The most significant differences (that were not concretely explored here) appear to be that Go has stricter limitations on retroactively implementing interfaces for existing types than the other languages. Whereas Rust (with some minor restrictions), and Swift allow the implementation of an interface by some type to be accomplished independently from the type's definition site. Rust and Swift thereby overcome Haveraaen et al.'s critique [5] of Java regarding this point. In fact, it is *interface inheritance* which makes the uniform polymorphic treatment of both intrinsic and user-defined types possible in the first place in Rust and Swift, that Haveraaen et al. seem to also (rightly) demand. In the following we will make some final comments on the differences in all these languages' generics features.

3.4.1 Go

Go's basic model to implement generics allows structures, interfaces, and ordinary functions, but not methods, to be given their own generic type parameters. The lack of true generic methods makes some duplication of instantiation code in clients unavoidable. Nevertheless, generic Go code is quite easy to read and to understand. What sets Go apart from the other languages is its built-in, easy to use support for conversion to generic types, and especially its brilliant new notion to interpret interfaces as type sets, along with its syntax to support this notion. This enables the Go programmer to easily tailor constraints on generic types to his specific needs, which is what makes the use of generics in Go pleasant. We consider these latter particular features of Go as "must haves" for Fortran.

3.4.2 Rust

Rust's basic model for generics is similar to Go's in that it allows for parameterization of structures, interfaces, and ordinary functions. Hence, what has been said above for Go in this respect holds also for Rust. Rust has, unfortunately, some quirks which render its use for the management of all types of dependencies through polymorphism somewhat sub-optimal when compared to the other languages considered here. The language is unpleasant to use, because of its "borrow checker", its *excessive* obsession with type safety, its employment of move semantics by default, and its overall C++-like philosophy to copiously rely on external dependencies, even for the most basic tasks, like initializing a generic type. The Rust version of our test case is therefore marred by some dependencies on external libraries, which is somewhat contrarian to the purpose of programming in a polymorphic fashion, namely to avoid rigid dependencies. But even with the functionality provided by such external dependencies, Rust doesn't allow type conversion to generic types within generic routines. A necessary capability for numerical work that is, for instance, built into Go. The points we like most about the language are its idea to decouple trait implementations from a `struct`'s definition through explicit `impl` blocks, and the complete control over the use of dynamic vs. static dispatch that Rust affords the programmer. These are particular features of Rust that, in our opinion, Fortran should borrow in some form.

3.4.3 Swift

Swift's basic model of implementing generics by allowing parameterized structures, functions, and methods (but not parameterized interfaces) is both the easiest to read, and the easiest to use from a programmer's perspective. Swift's generics design allows the Swift compiler to instantiate generics largely automatically, through inspection of the argument types that are passed to functions, methods, and (structure or class) constructors. In contrast to the other languages, in Swift, the user basically never has to bother with instantiating any generics.

If the Swift programmer knows how to write generic functions, his knowledge automatically translates into coding generic methods, since generic functions can be transformed into generic methods without requiring any changes to their function signatures. This property is helpful for the refactoring of non-OO codes into corresponding OO versions.

We hence consider Swift's generics to be the most attractive model to base Fortran's basic generic capabilities on, provided that it can be implemented sufficiently easily. The fact that Swift is a language that does not put emphasis on numerics, and whose present standard library therefore does not provide a truly useful `Numeric` protocol (that supports all the usual numeric operations), is of absolutely no consequence for adopting Swift's basic generics design for Fortran.

Fortran will necessarily do a better job in this respect, both by borrowing Go's idea of interpreting type sets as interfaces, so that the user can easily implement his own type constraints. But also by making accessible to the user a set of language-built in interfaces that are truly useful for numeric operations, and are implemented by Fortran's intrinsic types.

Chapter 4

Fortran additions I: Subtyping

The present and the next chapter describe additions to Fortran that we consider essential in order to enable dependency management through polymorphism at a level of functionality that is on par with modern languages like Swift, Rust, or Go.

4.1 Named abstract interfaces (traits)

The most important of the following additions is the capability to define named abstract interfaces, or traits (i.e. named collections of procedure signatures), and to declare instance variables of them. Named abstract interfaces are the crucial feature that is required in order to uniformly and properly express both run-time and compile-time polymorphism (i.e. generics) in the language, and to thereby enable a uniform management of dependencies on both user-defined *and* language-intrinsic types.

4.1.1 Abstract interface definitions

Fortran already allows the programmer to define unnamed abstract interfaces, but in order to use these as types, named versions of them are required, as in the following example, that defines two such named interfaces, `IAddition` and `ISubtraction`, that are intended as abstract blueprints for actual implementations of two type-bound procedures, named `add` and `sub`:

```
1   abstract interface :: IAddition
2      subroutine add(self,b)
3         import; implicit none
4         class(IAddition), intent(inout) :: self
5         real,             intent(in)    :: b
6      end subroutine add
7   end interface
8
9   abstract interface :: ISubtraction
10     subroutine sub(self,b)
11        import; implicit none
12        class(ISubtraction), intent(inout) :: self
13        real,                intent(in)    :: b
14     end subroutine sub
15  end interface
```

Since this is a simple addition to Fortran, that merely aims to further extend the use cases of abstract interfaces in the language (which presently serve as bounds on the signatures of procedure pointers, and `deferred`, i.e. abstract, methods), it is fully backwards compatible.

4.1.2 Variable declarations

Named abstract interfaces/traits are types in their own right. Their purpose is to allow the programmer to declare variables in terms of them. Either directly, i.e. as objects of such interfaces in run-time polymorphism, or as constraints on generic type parameters in compile-time polymorphism (see Sect. 5.3 for examples of the latter).

`Class` declaration specifier: enhancements

In order to use abstract interfaces to support run-time polymorphic objects through subtyping, Fortran's `class` specifier for variable declarations needs to be enhanced to accept named abstract interfaces, like in the following two examples:

```
1  class(IAddition), allocatable :: adder
2  class(IAddition), pointer     :: adderptr
```

The semantics here are that whenever a named abstract interface appears within the `class` specifier of an object's declaration, then all the `public` methods of that object, whose signatures are prescribed by an adopted interface like `IAddition` here, will make use of late binding. That is, their calls will be resolved by the run-time system of the language (e.g. through a virtual method table). In accordance with how objects that make use of run-time polymorphism through subclassing (i.e. implementation inheritance) are declared in the present Fortran standard, also "trait objects" (like `adder` or `adderptr` in the example above) must either be declared using the `allocatable`, or the `pointer` attribute, or they must be arguments to a procedure (as in the example of Sect. 4.1.1). The proposed additions are therefore backwards compatible with the functionality that is already available in the present language.

`Class` declaration specifier: constraints

Since the `class` declaration specifier is undefined for intrinsic types, and since the aforementioned semantics of this specifier imply late binding of methods (which is incompatible with intrinsic types), a compiler will need to ensure that the `class` declaration specifier is not used in conjunction with interfaces that admit language intrinsic types, like the empty interface, `IAnyType`, or any interfaces that are formulated in terms of type sets, as they are discussed in Sect. 5.1.2.

4.1.3 Extends specifier for abstract interfaces

Abstract interface definitions must allow the programmer to declare new abstract interfaces that are the union of *multiple* simpler ones (multiple interface inheritance). In the following example, the interface `IBasicMath` inherits the procedure signatures contained in both the interfaces `IAddition`, and `ISubtraction`, making `IBasicMath` at the same time a *subtype* of both these simpler interfaces. That is, objects that adopt or implement the `IBasicMath` interface (i.e. conform to it), can also be used in settings that require conformance to either the `IAddition`, or `ISubtraction` interfaces.

```
   abstract interface, extends(IAddition,ISubtraction) :: IBasicMath
   end interface
```

4.1.4 Short-hand notation for union of abstract interfaces

There are often cases where the union of two (or more) interfaces is required but where one would not like to go through the labor to explicitly set up a separate derived interface, like `IBasicMath` above. This can be useful in variable declarations. In such cases, it should be possible to specify the following

```
   class(IAddition + ISubtraction), allocatable :: addsub
```

instead of having to explicitly derive `IBasicMath` from `IAddition` and `ISubtraction`, as above, and then use it as follows:

```
   class(IBasicMath), allocatable :: addsub
```

4.2 Multiple interface inheritance for types

The language must make it possible not only for named abstract interfaces to conform to other named abstract interfaces, but also for *other types* to do the same, regardless of whether such types are user-defined or intrinsic to the language.

4.2.1 `Implements` specifier for derived type definitions

User-defined (i.e. derived) types can be made to conform to an interface by introducing an `implements` specifier for derived type definitions. In the following example the derived type `BasicMath` implements (i.e. conforms to, or adopts) the interface `IBasicMath` that was defined above

```
module basic
   ...

   type, implements(IBasicMath) :: BasicMath
      private
      real :: a
   contains
      procedure, public, pass(self) :: add
      procedure, public, pass(self) :: sub
   end type BasicMath

contains

   subroutine add(self,b)
      class(BasicMath), intent(inout) :: self
      real,             intent(in)    :: b
      self%a = self%a + b
   end subroutine add

   subroutine sub(self,b)
```

```
21        class(BasicMath), intent(inout) :: self
22        real,             intent(in)    :: b
23        self%a = self%a - b
24     end subroutine sub
25
26  end module basic
```

by providing implementations of all the method signatures that are contained in that interface. Notice, how `BasicMath`, by virtue of being an implementer of `IBasicMath`, is now also an implementer of `IAddition`, and `ISubtraction`. Hence, `BasicMath` can be used in client code that requires conformance to either one of the interfaces `IBasicMath`, `IAddition`, or `ISubtraction`.

It is crucial, for flexibility, that the above interface inheritance mechanism allow for a type to implement *multiple* different interfaces. For instance, if one wouldn't have defined the interface `IBasicMath` from above, and would nevertheless need to use objects of type `BasicMath` in settings that require conformance to either the `IAddition`, or `ISubtraction` interfaces, then the language must allow one to define type `BasicMath` as follows (skipping, for brevity, the implementation of the actual methods, that would be done exactly as in the previous example):

```
1     ...
2     type, implements(IAddition,ISubtraction) :: BasicMath
3     contains
4        procedure, public, pass(self) :: add
5        procedure, public, pass(self) :: sub
6     end type BasicMath
7     ...
```

In case the "implementing" type is `abstract`, it is allowed to provide an only partial implementation of the interface(s) that it adopts. However, any non-abstract type that is derived from this abstract type through implementation inheritance (subclassing) must then provide a full implementation.

4.2.2 `Implements` statement

In order to avoid having to wrap existing types into wrappers, when unforeseen new use cases result, it should be possible (as in Swift or Rust) to make any type implement new interfaces retroactively, regardless of where its original type definition is located. It would be desirable to provide such a capability for both user-defined and language intrinsic types, which would mean that methods would have to be allowed also for *intrinsic* types. The `implements` statement that is described below is aimed at ultimately accomplishing these capabilities, but for the purpose of a first prototype implementation it has been restricted here to provide such functionality for user-defined types *only*, i.e. its use on intrinsic types is presently prohibited.

Notice, that the `implements` statement has *no* relation to subclassing, i.e. one derived type being extended into another through (rigid) implementation inheritance. Rather, this is a feature that adds new capabilities to a single, *given* type. The feature is modeled after the "`extension`" feature of Swift, where it is used to enable retroactive implementation of new methods, additional constructors, and especially new interfaces for types, in order to dynamically change an *interface inheritance hierarchy*, and achieve utmost code flexibility.

Swift's `extension` blocks fulfill essentially the same purpose as Rust's `impl` blocks in this respect. They have been simplified here, and adjusted to Fortran's syntax that binds methods to

types through declaration blocks, rather than by including the actual implementation bodies themselves into such a block (the implementations need to be supplied as module procedures, as is usual in Fortran). The syntax of the feature is largely symmetric to that of the "`contains`" section of derived type definitions. Most of the options that are allowed for type-bound procedure declarations in derived type definitions, are therefore also allowed for such declarations within an `implements` statement.

Retroactively adding methods to a type

Suppose that we would like to add, from within a different module, two more methods to the `BasicMath` type from above, in order to give this type some additional functionality. This can be done using an `implements` *statement* as follows:

```
module enhanced

   use basic, only: BasicMath

   implicit none

   implements :: BasicMath
      procedure, public, pass(self) :: mul
      procedure, public, pass(self) :: div
   end implements BasicMath

contains
   ...
end module enhanced
```

where the actual implementations of the `mul` and `div` procedures would be given after the module's `contains` statement as usual.

Retroactively implementing interfaces by a type

Assume now that the purpose of our addition of the previous two methods was to actually make `BasicMath` conform to settings where implementations of multiplication with, or division by, a `real` are needed, and where the required functionality is described by two abstract interfaces called `IMultiplication` and `IDivision`. So far, we have added the code of the required methods, but we haven't made `BasicMath` pluggable into code that is written in terms of either one of these latter interfaces. To fix this, we simply state that the `BasicMath` type already has all of the required functionality, by acknowledging this using an `implements` statement for these two interfaces as follows:

```
   ...
   use enhanced, only: BasicMath

   implements (IMultiplication,IDivision) :: BasicMath
   end implements BasicMath
```

We could have also skipped the latter two code examples, to instead adopt the interfaces and provide the method implementations simultaneously, splitting the `implements` statements into two, to conform to one interface at a time, like so:

```
   ...
   use basic, only: BasicMath

   implements IMultiplication :: BasicMath
      procedure, public, pass(self) :: mul
   end implements BasicMath

   implements IDivision :: BasicMath
      procedure, public, pass(self) :: div
   end implements BasicMath
   ...
```

The result would have been the same. Such splitting of `implements` statements can be useful to improve readability, if different interfaces contain multiple procedure signatures, that would all have to be implemented. These two statements (together with the required implementations), could then even be distributed among different modules and files. Notice, also, how parentheses around interface lists in `implements` statements are optional, but not required.

4.3 Interoperability with subclassing

The present multiple interface inheritance (i.e. subtyping) features are interoperable with the single implementation inheritance (i.e. subclassing) that is already present in the language. That is, code examples like the following are possible:

```
   type :: Parent
   contains
      procedure :: method1
      procedure :: method2
   end type Child

   type, extends(Parent), implements(IChild) :: Child
   contains
      procedure :: method3
      procedure :: method4
   end type Child
   ...
```

Here, a `Child` type is defined, that inherits two methods (`method1` and `method2`) from a `Parent` type, and adds two further methods of its own (`method3` and `method4`), in order to conform to an interface, `IChild`, that consists of the signatures of all four of these methods. In such use cases, the `extends` specifier shall always precede the `implements` specifier.

Thus, the features described here are backwards compatible with the OO model that is used in the present language. Moreover, since the new `implements` specifier allows for inheritance of *multiple* interfaces (see above), this also fixes present Fortran's single inheritance limitations without introducing the potential ambiguities that multiple inheritance of implementation would cause (which are also known as "The Diamond Problem").

Chapter 5

Fortran additions II: Generics

The new subtyping features that were discussed in the previous chapter are required in order to uniformly express and support both run-time and compile-time polymorphism in Fortran. We will now proceed with discussing some enhancements that are required in order to further support compile-time polymorphism, i.e. generics.

5.1 Enhancements to Interfaces

5.1.1 Generic procedure signatures

Abstract interfaces should be allowed to contain signatures of generic procedures, as in Swift. The approach taken in Go and Rust to parameterize abstract interfaces themselves, appears not as attractive from a user's perspective. The following code shows, as an example, an abstract interface named `ISum` that contains the signature intended for a generic type-bound procedure, named `sum`:

```
1   abstract interface :: ISum
2      function sum{INumeric :: T}(self,x) result(s)
3         import; implicit none
4         class(ISum), intent(in) :: self
5         type(T),     intent(in) :: x(:)
6         type(T)                 :: s
7      end function sum
8   end interface
```

The example illustrates the use of a generic type parameter, i.e. a meta-type, or a *type of types*. In this example, this type parameter is simply called `T`, and it is preceded by the name of an abstract interface that expresses a constraint on the type parameter. The proposed Fortran generics thus support "strong concepts", and can be fully type-checked by the compiler. Both, the type parameter and its constraint, are part of a generic type parameter list that is enclosed in curly braces, and follows immediately behind the procedure's name. Notice that, since `T` is a meta-type, the syntax used above, that deviates slightly from how Fortran's usual function arguments are declared, appears justified as it reflects that, in type parameters, one is dealing with different entities.

5.1.2 Type sets

In order to make the interface based generics facility easy to use for the programmer, it must be possible, as in the Go language, to define abstract interfaces as type sets. The following example shows the simplest form of such a type set, by defining an interface `INumeric`, for use as a generics constraint in the example of Sect. 5.1.1, in order to admit for the type parameter `T`, that was given there, only the (32 bits wide) standard `integer` type:

```
1    abstract interface :: INumeric
2       integer
3    end interface
```

Unions of types

More useful interfaces can be defined by specifying unions of types as a type set, as in the following example

```
1    abstract interface :: INumeric
2       integer | real(real64)
3    end interface
```

that defines interface `INumeric` such as to admit either the standard `integer` or the `real(real64)` type. The semantics of these type set constructs are that they implicitly define a *set of function signatures*, namely the signatures of the intersecting (common) set of all the operations/functions for which the listed intrinsic types provide implementations.

Kind parameters

As a further example, a potentially even more useful `INumeric` interface could be coded as follows:

```
1    abstract interface :: INumeric
2       integer(*) | real(*) | complex(*)
3    end interface
```

Notice how this makes use of both unions of types, and kind parameters for types to include all `integer`, `real`, and `complex` types, admitted by the language, in a single `abstract interface` constraint.

Empty interface

A particularly important case is the empty interface, that matches all types, because all types have at least zero methods:

```
1    abstract interface :: IAnyType
2    end interface
```

5.1.3 Implicit interfaces

For simple use cases, it should be optionally possible for the programmer to employ a shorter notation for declaring type constraints, than having to define a separate interface, like `INumeric` above, and to then use it as in Sect. 5.1.1. The following modification of interface `ISum`'s original declaration of Sect. 5.1.1, provides such an example:

```
   abstract interface :: ISum
      function sum{integer | real(real64) :: T}(self,x) result(s)
         import; implicit none
         class(ISum), intent(in) :: self
         type(T),     intent(in) :: x(:)
         type(T)                 :: s
      end function sum
   end interface
```

The notation within the generic type parameter list defines an abstract interface implicitly, to be used as a type constraint for type `T`. In this particular case, to admit only the default `integer`, or `real(real64)` types, for `T`, as discussed above.

5.1.4 Predefined interfaces

The language should ideally supply a collection of predefined, commonly used generic constraints in the form of abstract interfaces that are contained in a language intrinsic module, tentatively called `generic_constraints` here. The actual code of these interfaces could then employ the "interfaces-as-type-sets" syntax that was described above, or any other suitable means. The list of such predefined interfaces should include

- an empty interface of the name `IAnyType` (as shown above),
- a general interface for numeric operations, `INumeric`, but also
- separate interfaces for all the language's numeric and relational operators.

The latter interfaces are required for the user to formulate selective generics constraints for intrinsic types. But also in order to enable the programmer to implement these operators himself for any new types where this would be desirable, or where these operators are not supported by default.

Language provided interfaces could then be imported from user code through a `use` statement like in the following example for `INumeric`:

```
module user_code

   use, intrinsic :: generic_constraints, only: INumeric

   abstract interface :: ISum
      function sum{INumeric :: T}(self,x) result(s)
         import; implicit none
         class(ISum), intent(in) :: self
         type(T),     intent(in) :: x(:)
         type(T)                 :: s
      end function sum
   end interface

end module user_code
```

They could be used as constraints in function and derived type implementations, or in other interfaces, like `ISum` here, that requires the functionality of `INumeric`.

5.2 Built-in facility for conversion to generic types

A language like Fortran, that is intended for numeric use, where conversions between different numeric types are required rather frequently, must allow conversions to generic types to be done as easily as it is the case in the Go language. By means that are built into the language, without having to rely exclusively on external library functionality.

For instance, generic routines will often have to initialize the result of reduction operations, as it is, e.g., the case in the test problem implementation of Sect. 2.2. There, a variable for summation needs to be initialized to the zero constant of type `T`. In Go, it is easily possible to express this initialization by transforming the (typeless) zero constant, `0`, into the corresponding constant of type `T`, i.e. by simply writing `s = T(0)`.

If, for instance, `T` is then instantiated at compile time with the `float64` type, the expression `T(0)` will be transformed by the compiler into `float64(0)`, i.e. a call to the correct conversion function. In Fortran's case, the compiler would have to translate the above expression into the intrinsic function call `real(0,kind=real64)`, which should actually be easy to do, also for all other cases where such conversion is indeed possible. Otherwise, the compiler should emit an error message, and abort compilation at the generics instantiation step.

5.3 Generic type parameters

As already mentioned above, Fortran's basic generics design should follow Swift's, if possible, and allow both ordinary and type-bound procedures (i.e. methods), and derived types to be given their own generic type parameters.

5.3.1 Procedures

Using the syntax proposed in this document, an implementation of a Fortran function for array summation that is generic over the type of its input array argument would look as follows:

```
1    function sum{INumeric :: T}(x) result(s)
2       type(T), intent(in) :: x(:)
3       type(T)             :: s
4       integer :: i
5       s = T(0)
6       do i = 1, size(x)
7          s = s + x(i)
8       end do
9    end function sum
```

Generic subroutines can be coded completely analogously.

5.3.2 Methods

The same algorithm as that of Sect. 5.3.1, when implemented as a generic method, `sum`, that is bound to a derived type named `SimpleSum`, which implements the interface `ISum` as it was given in Sect. 5.1.1, would instead look as follows:

```
1  module simple_library
2     ...
```

```
3
4     type, public, implements(ISum) :: SimpleSum
5     contains
6        procedure :: sum
7     end type SimpleSum
8
9  contains
10
11    function sum{INumeric :: T}(self,x) result(s)
12       class(SimpleSum), intent(in) :: self
13       type(T),          intent(in) :: x(:)
14       type(T)                      :: s
15       integer :: i
16       s = T(0)
17       do i = 1, size(x)
18          s = s + x(i)
19       end do
20    end function sum
21
22 end module simple_library
```

5.3.3 Derived types

In addition to procedures, and methods, generic type parameter lists must also be allowed for derived type definitions, as in the following example, in which the same interface `ISum` from above is implemented by another derived-type, named `PairwiseSum` (here, using an `implements` *statement*):

```
1  module pairwise_library
2     ...
3     type, public :: PairwiseSum{ISum :: U}
4        private
5        type(U) :: other
6     end type PairwiseSum
7
8     implements ISum :: PairwiseSum{ISum :: U}
9        procedure :: sum
10    end implements PairwiseSum
11
12 contains
13
14    function sum{INumeric :: T}(self,x) result(s)
15       class(PairwiseSum{U}), intent(in) :: self
16       type(T),               intent(in) :: x(:)
17       type(T)                           :: s
18       integer :: m
19       if (size(x) <= 2) then
20          s = self%other%sum(x)
21       else
```

```
22          m = size(x) / 2
23          s = self%sum(x(:m)) + self%sum(x(m+1:))
24        end if
25    end function sum
26
27 end module pairwise_library
```

Type `PairwiseSum` depends on a generic type parameter `U`, that is used within `PairwiseSum` itself in order to declare a field variable of `type(U)`, which is named `other`. As is indicated by the type constraint on `U`, object `other` conforms to the `ISum` interface itself, and therefore contains its own implementation of the `sum` procedure.

The above example furthermore demonstrates, how a derived type's generic parameters are brought into the scope of its type-bound procedures via the latters' passed-object dummy arguments. In this example, type `PairwiseSum`'s method, `sum`, has a passed-object dummy argument, `self`, that is declared being of `class(PairwiseSum{U})`. Hence, method `sum` can now access `PairwiseSum`'s generic parameter `U`. This allows the method to make use of two independently defined generic type parameters, `T` and `U`, which grants it increased flexibility. This also means that there is *no* implicit mechanism of bringing generic parameters of a derived type into the scope of its methods. If a type-bound procedure needs to access the generic parameters of its derived type, it must be provided with a passed-object dummy argument.

Notice, finally, that the declaration `class(PairwiseSum{U})` does not imply any ambiguities or contradictions with respect to compile-time vs. run-time polymorphism, because substitution semantics apply. At compile time, the compiler will substitute a set of different actual arguments for the generic parameter `U`. Hence, the notation `PairwiseSum{U}` really refers to a set of multiple, related, but *different* `PairwiseSum` types, whose *only* commonality is that they all implement the `ISum` interface (and furthermore contain different field components that do the same). Of course, passed-object dummy arguments of any of the different `PairwiseSum` types of this set can then be run-time polymorphic, in exactly the same manner that passed-object dummy arguments of other derived types that implement the same interface can be run-time polymorphic.

5.4 Updated structure constructors

If a derived type is parameterized over a generic type, as in the example of Sect. 5.3.3, then its structure constructor must also be assumed to be parameterized over the same generic type. Hence, calls of structure constructors that are instantiated with particular argument types replacing the generic type parameters of their derived types, like in the following initialization of an object called `drv`,

```
1 drv = PairwiseSum{SimpleSum}()
```

must be legal. As in Sect. 5.3.2, `SimpleSum` would be a derived type that implements the `ISum` interface, but (in contrast to the `PairwiseSum` type) is not parameterized by any generic type parameter itself.

We also propose to make a further, small, but important addition to structure constructors: namely to introduce the notion that a structure constructor is implicitly defined within the same scope that holds the definition of its derived type. Assuming that this scope is a module, then the structure constructor will always be able to access all the components of its derived type, even if these are declared being `private` to the module's scope. Hence, these components could

be initialized even by calls to the structure constructor that are being performed from outside the module's scope, in complete analogy to how user-defined constructors work in Fortran.

In this way, it would become possible to initialize `private`, `allocatable` derived type components by structure constructors, something that is crucial for concise OO programming. Since such an extension would merely add to the capabilities of the language, it would be fully backwards compatible. The elegance of the afore-given Go and Swift code versions, but also of the Fortran code examples that are presented in the next chapter is largely due to the use of such enhanced structure constructors. Lacking these, user-defined constructors would have to be used, leading to overly complex implementations, as e.g. in the Rust example code given in Listing 3.2.

5.5 Associated types

It is often the case, that a method signature needs to declare arguments that are of exactly the same generic types, over which its own derived type was parameterized. This problem can, in principle, be solved by making use of generic type parameters in both the derived type *and* its method, and then enforcing the consistency of these parameters, by passing the same type arguments to them during instantiation. A better solution, though, is to allow "associated types" to be declared within abstract interfaces, as it is possible in both the Rust and Swift languages.

The following example illustrates how an associated type is declared inside an abstract interface, `IAppendable`, that requires any implementing type to provide functionality for appending items to itself. These items are declared here to be of `type(Element)`, where `Element` is an alias, or placeholder, for any actual types that will be provided by implementations of that interface.

```
1  module vector_library
2
3     use, intrinsic :: generic_constraints, only: IAnyType
4
5     implicit none
6     private
7
8     abstract interface :: IAppendable
9        ! associated type "Element"
10       type, alias :: Element
11
12       subroutine append(self, item)
13          import; implicit none
14          class(IAppendable), intent(inout) :: self
15          type(Element),      intent(in)    :: item
16       end subroutine append
17    end interface
18
19    type, public, implements(IAppendable) :: Vector{IAnyType :: U}
20       private
21       type(U), allocatable :: elements(:)
22    contains
23       procedure :: append
24    end type Vector
25
```

```
26 contains
27
28    subroutine append(self, item)
29       class(Vector{U}), intent(inout) :: self
30       type(U),          intent(in)    :: item
31       self%elements = [self%elements, item]
32    end subroutine append
33
34 end module vector_library
```

An example of such an implementation of interface `IAppendable` is provided here by the derived type `Vector`, that stores an `elements` array of generic `type(U)`, where the type parameter `U` conforms to `IAnyType`. Notice, that in order to maintain consistency between the type of the `elements` array, and any new item that we wish to append to it, we must force the equally named `item` argument of method `append` to be of `type(U)` as well, as it is shown in this method's actual implementation. In order to be able to do this enforcement without contradicting interface `IAppendable`'s definition (that doesn't know anything about type `U`), we made use of the placeholder (i.e. associated) type `Element` in the latter interface. Given method `append`'s implementation, the compiler will then implicitly assign type `U` to the type alias `Element`, in order to conform to interface `IAppendable`'s definition.

5.6 Extensibility to rank genericity

Fortran's special role, as a language that caters to numeric programming, demands that any generics design for the language must allow for the possibility to also handle genericity of array rank. The present design offers a lot of room in this respect, but since this is a largely orthogonal issue, and since we consider a discussion of such functionality to be non-essential for the purpose of a very first prototype implementation of the generics features described here, we defer it to a separate document.

Chapter 6

Fortran versions of the test example

In order to comprehensively illustrate how the new features, that were discussed in the last two chapters, would be used in practice, we will give in the present chapter both complete functional and encapsulated (i.e. OO) Fortran code versions of the test problem that was used in our language survey.

6.1 Functional version

Fortran presently lacks support for advanced functional programming capabilities, like closures and variables of higher-order functions, that are, e.g., available in Go and the other modern languages. In contrast to the Go code version of Sect. 2.2, the functional Fortran code version that is presented in this section therefore makes no attempt to eliminate rigid dependencies on user-defined function implementations. The purpose of this functional Fortran version is merely to demonstrate how the new generics features can be used to eliminate rigid dependencies on language intrinsic types.

Despite these differences, there are a number of similarities to the Go code version of Listing 2.2, namely:

- We employ the (Go borrowed) syntax `integer | real(real64)`, to implement the interface `INumeric` as a type set, in order to express type genericity for the array `x`, that is input to all our different function implementations, and for the functions' return values.
- `INumeric` is defined by the user himself. Thus, there is no need for an external dependency.
- Conversions to generic types are done as in Go.

Listing 6.1: Proposed functional, generic Fortran version of the array averaging example.

```
1 module averager_library
2
3    use, intrinsic :: iso_fortran_env, only: real64
4
5    implicit none
6    private
7
8    public :: simple_average, pairwise_average
9
```

```
   abstract interface :: INumeric
      integer | real(real64)
   end interface

contains

   function simple_sum{INumeric :: T}(x) result(s)
      type(T), intent(in) :: x(:)
      type(T)             :: s
      integer :: i
      s = T(0)
      do i = 1, size(x)
         s = s + x(i)
      end do
   end function simple_sum

   function pairwise_sum{INumeric :: T}(x) result(s)
      type(T), intent(in) :: x(:)
      type(T)             :: s
      integer :: m
      if (size(x) <= 2) then
         s = simple_sum(x)
      else
         m = size(x) / 2
         s = pairwise_sum(x(:m)) + pairwise_sum(x(m+1:))
      end if
   end function pairwise_sum

   function simple_average{INumeric :: T}(x) result(a)
      type(T), intent(in) :: x(:)
      type(T)             :: a
      a = simple_sum(x) / T(size(x))
   end function simple_average

   function pairwise_average{INumeric :: T}(x) result(a)
      type(T), intent(in) :: x(:)
      type(T)             :: a
      a = pairwise_sum(x) / T(size(x))
   end function pairwise_average

end module averager_library


program main

   ! dependencies on implementations
   use averager_library, only: simple_average, pairwise_average

```

```
58    ! declarations
59    integer :: key
60
61    write(*,'(a)') 'Simple␣␣␣sum␣average:␣1'
62    write(*,'(a)') 'Pairwise␣sum␣average:␣2'
63    write(*,'(a)',advance='no') 'Choose␣an␣averaging␣method:␣'
64    read(*,*) key
65
66    select case (key)
67    case (1)
68       print '(i8)',   simple_average([1, 2, 3, 4, 5])
69       print '(f8.5)', simple_average([1.d0, 2.d0, 3.d0, 4.d0, 5.d0])
70    case (2)
71       print '(i8)',   pairwise_average([1, 2, 3, 4, 5])
72       print '(f8.5)', pairwise_average([1.d0, 2.d0, 3.d0, 4.d0, 5.d0])
73    case default
74       stop 'Case␣not␣implemented!'
75    end select
76
77 end program main
```

The example demonstrates that using the new generics features together with a functional programming style is easy, that the syntax is economical, and that automatic type inference for, and instantiation of, generics by the compiler should be straightforward and therefore reliable. Hence, we believe that the generics features described here will place no burden on the programmer.

6.2 Encapsulated versions

The present section will demonstrate that using the previously described new generics features seamlessly and easily in a modern-day OO programming setting is one of the great strengths of the present design. The equal importance that has been placed in this document on both proper compile-time and run-time polymorphic (i.e. modern-day OO) capabilities will allow for uniform dependency management of both language intrinsic and user-defined types in Fortran, that is on par with the most modern languages.

6.2.1 Dynamic method dispatch

Listing 6.2 shows our encapsulated Fortran code version of the test problem, that corresponds closest to the code versions that were presented in Chapter 3 for all the other languages.

- As in all these other versions, three interfaces are used to manage all the source code dependencies in the problem: `INumeric`, `ISum`, and `IAverager`.
- In contrast to the Go and Rust versions (Listings 3.1 and 3.2), none of the aforementioned interfaces is parameterized itself, since we followed Swift's basic model of generics.
- Interface inheritance is expressed through the presence of the `implements(...)` specifier in a derived-type definition (equivalent to Swift).

- The example code makes use, in the main program, of the new structure constructors, with their enhancements that were discussed in Sect. 5.4, for the classes `Averager`, `SimpleSum`, and `PairwiseSum`.
- This Fortran version makes use of modules and `use` statements with `only` clauses, in order to make explicit the source code dependencies of the different defined classes.

Listing 6.2: Proposed encapsulated Fortran version of the array averaging example.

```
module interfaces

   use, intrinsic :: iso_fortran_env, only: real64

   private

   public :: INumeric, ISum, IAverager

   abstract interface :: INumeric
      integer | real(real64)
   end interface

   abstract interface :: ISum
      function sum{INumeric :: T}(self,x) result(s)
         import; implicit none
         class(ISum), intent(in) :: self
         type(T),     intent(in) :: x(:)
         type(T)                 :: s
      end function sum
   end interface

   abstract interface :: IAverager
      function average{INumeric :: T}(self,x) result(a)
         import; implicit none
         class(IAverager), intent(in) :: self
         type(T),          intent(in) :: x(:)
         type(T)                      :: a
      end function average
   end interface

end module interfaces


module simple_library

   use interfaces, only: ISum, INumeric

   implicit none
   private

```

```
   type, public, implements(ISum) :: SimpleSum
   contains
      procedure :: sum
   end type SimpleSum

contains

   function sum{INumeric :: T}(self,x) result(s)
      class(SimpleSum), intent(in) :: self
      type(T),          intent(in) :: x(:)
      type(T)                      :: s
      integer :: i
      s = T(0)
      do i = 1, size(x)
         s = s + x(i)
      end do
   end function sum

end module simple_library


module pairwise_library

   use interfaces, only: ISum, INumeric

   implicit none
   private

   type, public, implements(ISum) :: PairwiseSum
      private
      class(ISum), allocatable :: other
   contains
      procedure :: sum
   end type PairwiseSum

contains

   function sum{INumeric :: T}(self,x) result(s)
      class(PairwiseSum), intent(in) :: self
      type(T),            intent(in) :: x(:)
      type(T)                        :: s
      integer :: m
      if (size(x) <= 2) then
         s = self%other%sum(x)
      else
         m = size(x) / 2
         s = self%sum(x(:m)) + self%sum(x(m+1:))
      end if
```

```
   end function sum

end module pairwise_library


module averager_library

   use interfaces, only: IAverager, ISum, INumeric

   implicit none
   private

   type, public, implements(IAverager) :: Averager
      private
      class(ISum), allocatable :: drv
   contains
      procedure :: average
   end type Averager

contains

   function average{INumeric :: T}(self,x) result(a)
      class(Averager), intent(in) :: self
      type(T),         intent(in) :: x(:)
      type(T)                     :: a
      a = self%drv%sum(x) / T(size(x))
   end function average

end module averager_library


program main

   ! dependencies on abstractions
   use interfaces,       only: IAverager

   ! dependencies on implementations
   use simple_library,   only: SimpleSum
   use pairwise_library, only: PairwiseSum
   use averager_library, only: Averager

   ! declarations
   integer :: key
   class(IAverager), allocatable :: avs, avp, av

   ! use of enhanced structure constructors
   avs = Averager(drv = SimpleSum())
   avp = Averager(drv = PairwiseSum(other = SimpleSum()))
```

```
137
138    write(*,'(a)') 'Simple   sum average: 1'
139    write(*,'(a)') 'Pairwise sum average: 2'
140    write(*,'(a)',advance='no') 'Choose an averaging method: '
141    read(*,*) key
142
143    select case (key)
144    case (1)
145       ! simple sum case
146       av = avs
147    case (2)
148       ! pairwise sum case
149       av = avp
150    case default
151       stop 'Case not implemented!'
152    end select
153
154    print '(i8)',   av%average([1, 2, 3, 4, 5])
155    print '(f8.5)', av%average([1.d0, 2.d0, 3.d0, 4.d0, 5.d0])
156
157 end program main
```

The most important point to notice in Listing 6.2 is how the main program is the only part of the code that (necessarily) depends on implementations. The *entire* rest of the code depends merely on (user-defined) abstract interfaces (see the `use` statements in the above modules). The features described in this document have enabled us to avoid rigidity in the program, by both decoupling it and making it operate on multiple data types, thus allowing for a maximum of code reuse. Notice, also, that (as in the functional Fortran implementation, i.e. Listing 6.1) not a single manual instantiation of generics is necessary anywhere in the code. The Fortran version described here is therefore as clean as the Go implementation of Listing 3.1 with respect to dependency management, and it is as easy to use, and to read and understand, as the Swift implementation of Listing 3.3.

6.2.2 Static method dispatch

One of the greatest benefits of the present design is that methods in OO programming can both be polymorphic, *and* be dispatched statically (as opposed to dynamically). This will enable inlining of polymorphic methods by the compiler, to potentially improve code performance. Listing 6.3 gives a *minimally* changed version of the encapsulated Fortran code of Listing 6.2, to effect static dispatch of the different `sum` methods.

The required changes are confined to a parameterization of the `PairwiseSum` and `Averager` derived types, by generic type parameters that are named `U`. These type parameters are then used in order to declare the field objects `other` and `drv` of these derived types, respectively, by means of the `type` specifier. This signifies compile-time polymorphism for these objects to the compiler (and hence static dispatch of their methods, as opposed to the `class` specifier that was used previously in order to effect run-time polymorphism and dynamic dispatch. See also Table 6.1 for a summary of rules regarding method dispatch).

Everything else, especially the declaration of these object variables as `alloctables` and their

instantiation at run-time using constructor chaining, was kept the same in order to demonstrate that static method dispatch does *not* necessarily mean that the actual object instances that contain the methods must be initialized and their memory allocated at compile-time (although in this particular case this is possible, as demonstrated in the next section, given that these objects do not contain any other `allocatable` data fields, like arrays). Notice also that none of the source code dependencies in the `use` statements have changed, i.e. the code is still fully decoupled, despite making now use of static dispatch.

Listing 6.3: Demonstrates static method dispatch for the `sum` methods.

```
module interfaces

   use, intrinsic :: iso_fortran_env, only: real64

   private

   public :: INumeric, ISum, IAverager

   abstract interface :: INumeric
      integer | real(real64)
   end interface

   abstract interface :: ISum
      function sum{INumeric :: T}(self,x) result(s)
         import; implicit none
         class(ISum), intent(in) :: self
         type(T),     intent(in) :: x(:)
         type(T)                 :: s
      end function sum
   end interface

   abstract interface :: IAverager
      function average{INumeric :: T}(self,x) result(a)
         import; implicit none
         class(IAverager), intent(in) :: self
         type(T),          intent(in) :: x(:)
         type(T)                      :: a
      end function average
   end interface

end module interfaces


module simple_library

   use interfaces, only: ISum, INumeric

   implicit none
   private
```

```
40
41    type, public, implements(ISum) :: SimpleSum
42    contains
43       procedure :: sum
44    end type SimpleSum
45
46 contains
47
48    function sum{INumeric :: T}(self,x) result(s)
49       class(SimpleSum), intent(in) :: self
50       type(T),          intent(in) :: x(:)
51       type(T)                      :: s
52       integer :: i
53       s = T(0)
54       do i = 1, size(x)
55          s = s + x(i)
56       end do
57    end function sum
58
59 end module simple_library
60
61
62 module pairwise_library
63
64    use interfaces, only: ISum, INumeric
65
66    implicit none
67    private
68
69    type, public, implements(ISum) :: PairwiseSum{ISum :: U}
70       private
71       type(U), allocatable :: other
72    contains
73       procedure :: sum
74    end type PairwiseSum
75
76 contains
77
78    function sum{INumeric :: T}(self,x) result(s)
79       class(PairwiseSum{U}), intent(in) :: self
80       type(T),               intent(in) :: x(:)
81       type(T)                           :: s
82       integer :: m
83       if (size(x) <= 2) then
84          s = self%other%sum(x)
85       else
86          m = size(x) / 2
87          s = self%sum(x(:m)) + self%sum(x(m+1:))
```

```
      end if
   end function sum

end module pairwise_library


module averager_library

   use interfaces, only: IAverager, ISum, INumeric

   implicit none
   private

   type, public, implements(IAverager) :: Averager{ISum :: U}
      private
      type(U), allocatable :: drv
   contains
      procedure :: average
   end type Averager

contains

   function average{INumeric :: T}(self,x) result(a)
      class(Averager{U}), intent(in) :: self
      type(T),            intent(in) :: x(:)
      type(T)                        :: a
      a = self%drv%sum(x) / T(size(x))
   end function average

end module averager_library


program main

   ! dependencies on abstractions
   use interfaces,       only: IAverager

   ! dependencies on implementations
   use simple_library,   only: SimpleSum
   use pairwise_library, only: PairwiseSum
   use averager_library, only: Averager

   ! declarations
   integer :: key
   class(IAverager), allocatable :: avs, avp, av

   ! use of enhanced structure constructors
   avs = Averager(drv = SimpleSum())
```

```
136     avp = Averager(drv = PairwiseSum(other = SimpleSum()))
137
138     write(*,'(a)') 'Simple   sum average: 1'
139     write(*,'(a)') 'Pairwise sum average: 2'
140     write(*,'(a)',advance='no') 'Choose an averaging method: '
141     read(*,*) key
142
143     select case (key)
144     case (1)
145        ! simple sum case
146        av = avs
147     case (2)
148        ! pairwise sum case
149        av = avp
150     case default
151        stop 'Case not implemented!'
152     end select
153
154     print '(i8)',   av%average([1, 2, 3, 4, 5])
155     print '(f8.5)', av%average([1.d0, 2.d0, 3.d0, 4.d0, 5.d0])
156
157 end program main
```

object declaration	dynamic dispatch	static dispatch
`class(Interface)`	always	never
`class(DerivedType)`	if `DerivedType` is `extended`	if `DerivedType` is `unextended`[1]
`type(DerivedType)`	never	always

Table 6.1: Correspondence between object declarations and method dispatch strategies.

As in corresponding Rust and Swift implementations of the test problem, the instantiation of the objects `other` and `drv` through constructor calls in the main program has the benefit that the compiler should be able to infer the correct type arguments that are required to automatically instantiate the involved generic derived types. Notice also, that in Listing 6.3, the `av` object of `IAverager` type still needs to make use of run-time polymorphism, because it is initialized in a `select case` statement by the main program. This object cannot be made to employ compile-time polymorphism, as it is initialized within a statement that performs a run-time decision.

As a final remark we'd like to emphasize that, on readability grounds, a coding style as that given in Listing 6.2 is generally preferable over that of Listing 6.3. The use of numerous generic type parameters can quickly make code unreadable. We'd therefore recommend the default use of run-time polymorphism for managing dependencies on user-defined types, and the employment of generics for this latter task only in cases where profiling has shown that static dispatch would significantly speed up a program's execution (by allowing method inlining by the compiler). Of course, the use of generics to manage dependencies on language intrinsic types remains unaffected by this recommendation.

[1] Or the method is declared as `non_overridable`.

6.2.3 Static method dispatch and static object declarations

In the present simple example, and taking Listing 6.3 as a baseline, it is actually possible to even avoid some of the run-time memory allocation overhead of the program, by having the field objects `other` and `drv`, that are contained within the `PairwiseSum` and `Averager` types, be statically declared. To accomplish this, the two lines

```
1   type(U), allocatable :: other
2   type(U), allocatable :: drv
```

in Listing 6.3 need to be replaced by the following two code lines:

```
1   type(U) :: other
2   type(U) :: drv
```

Correspondingly, the object instantiations that are to be carried out from the main program need to be changed from

```
1   avs = Averager(drv = SimpleSum())
2   avp = Averager(drv = PairwiseSum(other = SimpleSum()))
```

into the following two calls of `Averager`'s parameterized structure constructor (cf. Sect. 5.4), which must now be provided with the types `SimpleSum`, and `PairwiseSum` as generic type parameters:

```
1   avs = Averager{SimpleSum}()
2   avp = Averager{PairwiseSum{SimpleSum}}()
```

The full source code for this version of the test problem can be found in the `Code` subdirectory that is accompanying this document.

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