Abstract

We present endpoints, a library that provides consistent client implementation, server implementation and documentation from a user-defined communication protocol description. The library provides type safe remote invocations, and is modular and extensible. This paper shows how its usage looks like, highlights the Scala features that its implementation relies on, and compares it to other similar tools.

1 Introduction

Web applications, most smartphone applications and distributed applications have in common that they all involve remote communication between machines. A prerequisite for remote communication to work is that clients and servers speak the same protocol. In practice, developers often duplicate the details of such protocols between the client implementation, the server implementation and the public documentation (if any). This duplication increases the risk of inconsistencies and decreases the developer productivity.

Factoring out the parts of the protocol that are similar between clients and servers is hard because the tasks they perform are very different, and because they might be implemented in different projects or even different programming languages.

We present endpoints\(^1\), a library that:

- turns descriptions of communication protocols into consistent client implementation, server implementation and documentation;
- guarantees that requests are well constructed: it raises a compilation error if one invokes an endpoint but supplies incorrect data;
- is modular: multiple backends are available (Play framework, scalaj-http, akka-http, plain old XMLHttpRequest) and features can easily be made opt-in;

\(^1\)Source code is available at https://github.com/julienrf/endpoints
• is extensible: users can define application-specific descriptions of a particular aspect of the underlying protocol (e.g. authorization) as well as custom interpreters for descriptions.

In contrast with most of comparable libraries, endpoints is written in pure Scala and uses no macros nor code generation. Its implementation relies on object oriented programming features such as traits and abstract type members.

The remaining of this article is organized as follows: the next section details the problem addressed by endpoints, section 3 presents the library from a user point of view, section 4 explains how it is implemented and section 5 compares it to similar libraries.

2 Motivation

We can illustrate the duplication between client and server implementations of a same protocol with the following pseudo implementation of an HTTP server that exposes an endpoint to look up for a resource:

```scala
val getItem : Request => Future[Response] = {
  case GET(p*/item/$id") =>
    itemsRepository.lookup(id)
      .map(item => Ok(item.asJson))
}
```

The corresponding pseudo implementation of a matching HTTP client could be as follows:

```scala
val getItem : String => Future[Item] = id =>
  httpClient.get("/item/${urlEncode(id)}")
    .map(_.entity.fromJson[Item])
```

The details of the underlying protocol that the server and the client have to agree on are the HTTP verb (GET), the request path (/item/ followed by an id), and the JSON representation of the resource.

We observe that these elements are duplicated in the server and client implementations. However abstracting over them is hard because the tasks performed by the client and the server are very different. For instance, the client uses the id to build the URL of the request, whereas the server extracts the id from the URL of an incoming request.

Furthermore, if the application has a public API, developers have to repeat again the details of the protocol in documentation. Here is an example of an OpenAPI² definition for the getItem endpoint:

```
/ item / { id }:
  get:
    description: Get an item
    responses:
      200:
        description: The item identified by 'id'
        content: application/json
```

²https://www.openapis.org/
Again, we see that the HTTP verb, the URL format and the response type are repeated in the document.

Ideally, we want users to write these elements only once and make the client, the server and the documentation reuse them. The next section shows how users can achieve this with the *endpoints* library.

## 3 *endpoints* in a Nutshell

### 3.1 Description vs Interpretation

First, users describe the details of the communication protocol. For instance, the description of our `getItem` endpoint looks as follows:

```scala
val getItem: Endpoint[String, Item] =
  endpoint(
    get(path / "item" / segment[String]),
    jsonResponse[Item]
  )
```

This description defines that the used HTTP verb is *GET*, the format of the URL is `/item/` followed by a text segment (the item id), and that the response uses the JSON content-type.

The type of the `getItem` member is `Endpoint[String, Item]`. As this will be illustrated in the next section, this type is abstract and has a different meaning in the context of the client, the server or the documentation.

### 3.2 Type Safe Remote Calls

The library provides a client implementation for the above endpoint description. Its usage looks as follows:

```scala
val item: Future[Item] = getItem("abc123")
```

From the client point of view, `getItem` is a function that takes as parameter the required information to build the request (in our case, the item identifier) and eventually returns the `Item` instance.

The `getItem` implementation encodes the parameters (the item id), performs the HTTP request and decodes the JSON response. If a user tries to invoke the `getItem` function with a parameter of the wrong type (e.g. an `Int`), a compilation error is raised.

The *endpoints* library also provides a server for the endpoint description. Its usage looks as follows:

```scala
getItem.implementedByAsync { (id: String) =>
  itemsRepository.lookup(id)
}
```

From the server point of view, `getItem` is an object that has an `implementedByAsync` method, which takes as parameter the business logic performing the lookup. The result of the `implementedByAsync` call is a *request handler*: a function that decodes information from incoming requests that match...
the URL and HTTP verb of the endpoint description, invokes the business logic, and builds an HTTP response by encoding the returned Item instance in JSON.

We see that with the endpoints library, the details of the underlying communication protocol are not duplicated anymore between the client and the server.

### 3.3 Modularity

In the above example, the `getItem` definition uses methods (`endpoint`, `path`, `jsonResponse`, etc.) that are provided by traits. The whole definition looks as follows:

```scala
trait Descriptions extends Endpoints with JsonEntities {
  val getItem = ...}
```

The traits `Endpoints` and `JsonEntities` provide vocabulary (methods) to describe endpoints.

The client implementation extends the `Descriptions` trait and attaches a particular meaning to the vocabulary used to describe the endpoints:

```scala
object Client extends Descriptions with xhr.Endpoints with xhr.JsonEntities
```

The `xhr` package provides traits that implement the `Endpoints` and `JsonEntities` traits with a semantics of a client. They use the XMLHttpRequest API for communicating with the server.

The following diagram illustrates this architecture.

```
```

The fact that the client interpreter (in the `xhr` package) is decoupled from the vocabulary (in the `algebra` package) makes it easy, at use site, to isolate the endpoint descriptions in a module and then have the client, server or other interpreters in separate modules. Also, each interpreter can bring its own dependencies without affecting the descriptions.

In our example the `Endpoints` trait provides the base vocabulary to describe endpoints, and the `JsonEntities` enriches this vocabulary with concepts related to the JSON format. The `endpoints` library provides several other traits, each one providing vocabulary for a specific concern (e.g. authentication). We call such traits language units. The more language units a user uses, the more features are

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3The XMLHttpRequest API is available in web browsers and is used to perform HTTP requests.
available, but at the same time, the higher the effort to implement an interpreter for these features. The fact that language units are in separate traits allows us to implement partial interpreters: interpreters for a subset of the available language units.

3.4 Extensibility

Thanks to this modular design, users can easily introduce their own application-specific language units. To achieve this they first define a trait with abstract members introducing new vocabulary specific to their application:

```scala
trait Authorization extends Endpoints {
  type Authorized[A] = Response[Option[A]]
  def authorized[A](response: Response[A]): Authorized[A]
}
```

This trait might extend an existing language unit, depending on whether the user wants to reuse or not the features provided by this language unit.

Then, users can implement various interpreters for their language unit, by defining a trait that implements its abstract members:

```scala
trait ClientAuthorization extends Authorization with xhr.Endpoints ...
```

Again, an interpreter might reuse an existing interpreter infrastructure. In the above example, we reuse the `xhr` interpreter, so that our `ClientAuthorization` interpreter can be mixed to an existing stack of `xhr` interpreters to add the ability to interprete the `Authorization` language unit.

3.5 First Class Citizen Descriptions

In contrast with some similar tools (see section 5), language units are embedded DSLs[3]: descriptions of endpoints are not purely data (e.g. a JSON or XML dialect), but they are Scala code, which means that all the means of abstraction of the Scala language can be freely used. For instance, one can define a `val` to hold a part of a description that is going to be reused for several endpoint definitions.

4 Implementation

4.1 Overall Pattern

In essence, language units and interpreters are algebra interfaces and object algebras [5], respectively. Concepts introduced by language units (e.g. request, URL, query string) are modeled with a corresponding abstract type. In practice the `Endpoints` language unit defines 12 such concepts. In order to simplify the signature of traits defining language units, we use the encoding proposed by Hofer et. al.[2] where type carriers are modeled with abstract type members instead of type parameters.
For instance, the `Endpoints` trait that introduces an abstract method `get`, which returns a `Request[A]`, is defined as follows:

```scala
package algebra
trait Endpoints {
  type Url[A]
  type Request[A]
  def get[A](url: Url[A]): Request[A]
}
```

We omitted the methods that make it possible to create `Url[_,_]` instances for the sake of brevity.

The type `Request[A]` represents a request that carries an information of type `A`. For instance, a request containing an id of type `Long` would have type `Request[Long]`. Similarly, a request containing two parameters, one of type `Int` and one of type `String`, would have type `Request[(Int, String)]`, and so on for other arities.

The method `get` describes an HTTP request that uses the verb `GET`.

In summary, language units introduce concepts (abstract type members) and ways to create or combine them (abstract methods).

Interpreters give a concrete meaning to these concepts. For instance, the `xhr` interpreter embodies the client side of a request:

```scala
package xhr
trait Endpoints extends algebra.Endpoints {
  type Request[A] = A => XMLHttpRequest
}
```

We omitted the implementation of the methods for the sake of brevity.

From the point of view of this client, a `Request[A]` is a function that takes an `A` and returns an `XMLHttpRequest` instance. In this case, the `A` information is what is needed to build the request.

The server interpreter is defined like so:

```scala
package playserver
trait Endpoints extends algebra.Endpoints {
  type Request[A] = RequestHeader => Option[BodyParser[A]]
}
```

For this server interpreter (backed by Play framework), a `Request[A]` is a function checking that an incoming request matches the description, and in such a case returns an object that extracts an `A` from the request.

### 4.2 Forwarding Interpreters

As mentioned in the introduction, the `endpoints` library is also able to generate an OpenAPI documentation from endpoint descriptions. However, the language units used to describe the endpoints can not be the same as those used so far, because documentation needs additional information (such as human-readable descriptions).

As an example, here is how one would write the `getItem` definition using these language units:
val getItem : Endpoint[String, Item] =
  endpoint(
    get(path / "item" / segment[String]("id")),
    jsonResponse[Item]({
      documentation = "The item identified by 'id'
    })
  )

This listing is similar to the one given in section 3.1 but some methods take additional parameters (e.g. there is a documentation parameter in the jsonResponse method) that are used to generate the documentation.

Since the language unit is different from the one presented in section 3.1, we can not apply the client and server interpreters to it. However, being able to reuse these interpreters on such descriptions is useful, that’s why we implemented a solution based on forwarding[1]:

```
The doc.forward package provides interpreters for doc.algebra language units. These interpreters are implemented by forwarding calls to an algebra interpreter. It is worth noting that this relationship can be refined when language units are refined (i.e. the receiver member of the doc.forward.JsonEntities interpreter refers to an algebra.JsonEntities interpreter).

For instance, here is an excerpt of the implementation of the doc.forward.Endpoints interpreter:

trait Endpoints extends doc.algebra.Endpoints {
  val receiver : algebra.Endpoints
  type Request[A] = receiver.Request[A]
  type Url[A] = receiver.Url[A]
  def get[A](url: Url[A]): Request[A] = receiver.get(url)
}
```

For users, applying the xhr client interpreter to documented descriptions looks as follows:

```
object Client extends DocDescriptions
  with forward.Endpoints
  with forward.JsonEntities {
    lazy val receiver = new xhr.Endpoints with xhr.JsonEntities
  }
```
5 Related Works

5.1 Autowire / Remotely / Lagom

Autowire\(^4\) and Remotely\(^5\) are Scala libraries automating remote procedure calls between a server and a client. Lagom\(^6\) is a framework for implementing microservices. One difference with endpoints is that these tools are based on macros generating the client according to the interface (defined as a Scala trait) of the server. These macros make these solutions harder to reason about (since they synthesize code that is not seen by users) and their implementation might not support all edge cases\(^7\).

A more fundamental difference is that in Autowire and Remotely, the underlying HTTP communication is viewed as an implementation detail, and all remote calls are multiplexed through a single HTTP endpoint. In contrast, the goal of endpoints is to embrace the features of the HTTP protocol (content negotiation, authorization, semantic verbs and status codes, etc.), so, in general, one HTTP endpoint is used for one remote call (though the library also supports multiplexing in case users don’t care about the underlying HTTP protocol).

Last, Autowire, Remotely and Lagom can not generate documentation of the communication protocol.

5.2 Swagger / Thrift / Protobuf

Solutions such as Swagger, Thrift and Google Protocol Buffers generate the client and server code based on a protocol definition. We believe that generated code is hard to reason about and to integrate and keep in sync with code written by developers. Also, the protocol is defined in a dedicated language (JSON dialect or custom language) which is not extensible and not as convenient as using a fully-blown programming language like Scala.

5.3 Rho / Fintrospect

Fintrospect\(^8\) and Rho\(^9\) are the libraries closest to endpoints. Their features and usage are similar: users describe their communication protocol in plain Scala and the library generates client (Fintrospect only), server and documentation. The key difference is that the communication protocol is described by a sealed AST, which is not extensible: users can not extend descriptions with application-specific concerns and interpreters can not be partial.

\(^4\)https://github.com/lihaoyi/autowire
\(^5\)http://verizon.github.io/remotely
\(^6\)https://www.lagomframework.com/
\(^7\)Several issues have been reported about macro expansion: https://goo.gl/Spc07u, https://goo.gl/F2E5Ev and https://goo.gl/LCmVr8
\(^8\)http://fintrospect.io/
\(^9\)https://github.com/http4s/rho
5.4 Servant

Servant[4] is a Haskell library that uses generic programming to derive client, server and documentation from endpoint descriptions. The descriptions and interpreters are extensible. The difference with endpoints is that in Servant descriptions are types, whereas in endpoints they are values.

Using types as descriptions has some benefits: they can directly be used to type instances of data (in contrast, in endpoints descriptions of data types have to mirror a corresponding type definition). On the other hand, we believe that abstracting and combining types using type-level computations is, in general, less convenient for users.

6 Conclusion

We presented endpoints, a modular and extensible library to perform remote communication in Scala. Its implementation mainly relies on the object oriented features of the language such as abstract methods, abstract type members and multiple inheritance.

References

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[4] Alp Mestanogullari, Sönke Hahn, Julian K Arni, and Andres Löh. Type-level web apis with servant. In Proceedings of the 11th ACM SIGPLAN Workshop on Generic Programming. ACM, 2015.

[5] Bruno C. d. S. Oliveira and William R. Cook. Extensibility for the Masses, pages 2–27. Springer Berlin Heidelberg, Berlin, Heidelberg, 2012.