Choreographies as Objects

SAVERIO GIALLORENZO, University of Southern Denmark, Denmark
FABRIZIO MONTESI, University of Southern Denmark, Denmark
MARCO PERESSOTTI, University of Southern Denmark, Denmark

We present Choral, the first framework for programming choreographies (multiparty protocols) that builds on top of mainstream programming abstractions: in Choral, choreographies are objects. Given a choreography that defines interactions among some roles (Alice, Bob, etc.), an implementation for each role in the choreography is automatically generated by a compiler. These implementations are libraries in pure Java, which developers can modularly compose in their own programs to participate correctly in choreographies.

1 INTRODUCTION

Background. Choreographies, broadly construed, are coordination plans for concurrent systems based on message passing [Object Management Group 2011; W3C 2004]. In software development, programmers use choreographies to agree on the interactions that communicating endpoints should enact to achieve a common goal; then, the programming of each endpoint can proceed independently. The success of this development process hinges on achieving choreography compliance: when all endpoints are run together, they interact as defined by the choreographies agreed upon (Figure 1).

![Fig. 1. Choreography compliance: endpoints should communicate as intended by the choreographies that they engage in.](image1)

Achieving choreography compliance is hard: predicting how multiple programs will interact at runtime is challenging [O’Hearn 2018], and mainstream tools do not adequately support programmers in reasoning about coordination in their code [Leesatapornwongsa et al. 2016; Lu et al. 2008]. Additionally, choreographies are complex: besides defining communication flows among their roles (abstractions of endpoints, like “Alice”, “Bob”, “Buyer”, etc.) [Intl. Telecommunication Union 1996]; often, choreographies include computational details of arbitrary complexity, e.g., pre- or post-processing of data (encryption, validation, anonymisation, etc.), state information, or how
to choose among alternative behaviours. Examples of choreographies are distributed authentication protocols [OpenID Foundation 2014; Sporny et al. 2011], cryptographic protocols [Diffie and Hellman 1976], and multiparty business processes [Object Management Group 2011; W3C 2004].

In response to the challenge of choreography compliance, previous work investigated verification and synthesis approaches to relate choreographies to endpoint programs [Ancona et al. 2016; Autili et al. 2018; Basu et al. 2012; Hüttel et al. 2016; Qiu et al. 2007]. Among these approaches, choreographic programming makes choreography compliance tractable in the presence of arbitrary computational details in choreographies [Montesi 2013]. In this approach, choreographies are high-level programs and compliance is obtained by construction: given a choreography, a compiler automatically translates it to a set of compliant endpoint implementations. Choreographic programming has been shown to have promising potential in multiple contexts, including information flow [Lluch-Lafuente et al. 2015], distributed algorithms [Cruz-Filipe and Montesi 2016], cyber-physical systems [López and Heussen 2017; López et al. 2016], and self-adaptive systems [Dalla Preda et al. 2017].

The problem. The languages used to represent choreographies and endpoint programs in previous works, including choreographic programming, are based on behavioural models (process calculi, communicating automata, etc.). This makes it unclear how the results of these works can be applied in practice to mainstream programming, where the basic building blocks are different (data, functions, objects, etc.). The most notable and unfortunate consequence is that current programming frameworks for choreographic programming do not support modular software development [Dalla Preda et al. 2017; Montesi 2013]. Specifically, the code that these frameworks generate for each endpoint is a “black box” program without an API: it can be executed, but it is not designed to be composed by programmers within larger codebases. Thus, for example, the common scenario of programming an endpoint that participates in multiple choreographies is not supported, and neither is programming an endpoint where participating in a choreography is only part of what the endpoint does.

In summary, we still have to discover how the benefits of choreographic programming can be imported to mainstream software development. The aim of this article is to fill this gap.

This article. We present Choral, a new choreographic programming framework that supports modularity and is based on mainstream programming concepts. To demonstrate applicability, Choral is compatible with Java, but our ideas apply to most statically-typed object-oriented languages.

The fulcrum of Choral is a new interpretation of choreographies that builds naturally on top of existing language abstractions: in Choral, choreographies are objects. The starting point for this interpretation is a revisitation of the ideas in Lambda 5 [Murphy VII et al. 2004], the model that inspired the research line on multitier programming [Murphy VII et al. 2007; Neubauer and Thiemann 2005; Serrano et al. 2006; Weisenburger et al. 2018]. In Lambda 5, each data type is located at a place, enabling reasoning on spatially-distributed computation. Choral generalises these types from single to multiple locations, which allows us to express that an object is implemented choreographically: Choral objects have types of the form \( T_{\text{@}}(R_1, \ldots, R_n) \), where \( T \) is the usual interface of the object, and \( R_1, \ldots, R_n \) are the roles that collaboratively implement the object.

As an example, consider the case of a multiparty choreography for distributed authentication, where a service authenticates a client via a third-party identity provider. We can define such a choreography as a Choral object of type \( \text{DistAuth}_{\text{@}}(\text{Client, Service, IP}) \) (IP is short for identity provider). The object can implement methods that involve multiple roles. For example, it can offer a method \texttt{authenticate} with the following signature.

```
Optional@Service<AuthToken> authenticate(Credentials@Client credentials)
```

Choral Code
Invoking method `authenticate` with some `Credentials` located at `Client` returns an authorisation token at `Service` (Optional, since authentication might fail), denoting movement of data.

We leverage our choreographies-as-objects interpretation to develop a methodology for choreography compliance that supports modularity and is compatible with mainstream programming. We depict this methodology in Figure 2. Given the code of a Choral object with some roles, a compiler produces a compliant-by-construction software library in pure Java for each role (“coordination code” in the figure): each library contains the local implementation of what its role should do to execute the choreography correctly. These libraries offer Java APIs derived from the source choreographies, which reveal only the details pertaining the implemented role. When a software developer programs an endpoint that should engage in a choreography, they can just take the library compiled for the role that they want to play and use it through its Java API. Through such APIs, developers can modularly compose multiple libraries with their own code (“local code” in the figure), thus gaining the ability to participate in multiple choreographies.

The Java code compiled from method `authenticate` for role `Service` has the signature below.

```
Optional<AuthToken> authenticate()
```

Parameter `credentials` from the choreographic method has disappeared, since its type does not include `Service`; conversely, the return type `Optional<AuthToken>` remains.

**Contributions.** We outline our main contributions.

**Language.** We present Choral, the first choreographic programming language based on mainstream abstractions and interoperable with a mainstream language (Java). The key novelty of the Choral language is that data types are higher-kinded types parameterised on roles. We leverage this feature to bring the key aspects of choreographies to object-oriented programming (spatial distribution, interaction, and knowledge of choice). Choral is also the first truly higher-order choreography language, in the sense that choreographies passed as arguments can carry state.

**Type checker.** We implement a type checker that prevents coding errors related to roles, e.g., attempting a computation at a role using data at another role without performing an appropriate communication. Our typing supports the reuse of all existing Java classes and interfaces in We also extend typical aspects of typed objects to choreographies, including inheritance, method overloading, and semantic parametricity. This allows us to define in Choral the first hierarchy of “channel types” for choreographies, which specify topological assumptions in choreographies. Method overloading also allows us to specialise computation based on the role that performs it.

**Compiler.** We implement a compiler that translates Choral source into Java libraries that comply with the source choreography. Differently from previous work on choreographic programming, our compiler does not assume the presence of any fixed runtime middleware.

**Testing.** We present the first testing tool for choreographic programming. Since choreography implementations are spread over multiple components (one for each role), testing choreographies can be difficult because it calls for integration testing. Our testing tool leverages Choral to write “choreographic tests” that look like simple unit tests at the choreographic level, but are then compiled to integration tests that integrate the respective implementations of all roles.

**Evaluation.** We explore the expressiveness of our language with use cases of different kinds, covering security protocols, cyberphysical systems connected to the cloud, and parallel algorithms. Then, we carry out a systematic analysis, where the Choral compiler reduces the amount of code that programmers have to write from 50% up to almost 400%.
Outline. We overview Choral with simple examples in Section 2, and give more realistic use cases in Section 3. The syntax and implementation of Choral are discussed in Section 4, and testing in Section 5. We evaluate Choral systematically in Section 6. Related work is discussed in Section 7.

2 CHORAL IN PRACTICE

We start with an overview of the key features of Choral. First, spatial distribution: the expression of computation that takes place at different roles (Section 2.1). Second, interaction: the coding of data exchanges between roles (Section 2.2). Third, knowledge of choice: the coordination of roles to choose between alternative behaviours (Section 2.3).

The Choral language is quite big. Its usefulness depends on the capability to produce software libraries whose APIs look like "idiomatic" Java APIs, so we chose to incorporate a substantial set of features, which would commonly be considered necessary to use and produce Java APIs: Choral supports classes, interfaces, generics, inheritance, and method overloading. APIs generated by Choral support lambda expressions, in the sense that Java programmers can pass lambda expressions as arguments to our APIs. (Just as in Java, Choral sees these arguments as objects.) Supporting the Java syntax for lambda expressions inside of Choral programs is not necessary for our objective, since they can be encoded as objects, so we leave it to future work on ergonomics.

In the rest of this section, we explain the key aspects of Choral by assuming that the reader is familiar with Java. The reader can assume that language constructs that have the same syntax as Java behave as expected (modulo our additions, which we explain in the text).

2.1 Roles and data types

Hello roles. All values in Choral are distributed over one or more roles, using the @-notation seen in Section 1. The degenerate case of values involving one role allows Choral to reuse existing Java classes and interfaces, lifted mechanically to Choral types and made available to Choral code. For example, the literal "Hello from A"@A is a string value "Hello from A" located at role A. Code involving different roles can be freely mixed in Choral, as in the following snippet.

```java
class HelloRoles(A, B) {
    public static void sayHello() {
        String@A a = "Hello from A"; String@B b = "Hello from B";
        System@A.out.println(a); System@B.out.println(b); }
}
```

The code above defines a class, HelloRoles, parameterised over two roles, A and B. Line 3 assigns the string "Hello from A" located at A ("Hello from A"@A) to variable a of type "String at A" (String@A), and then the same but for a string located at B. Then, Line 4 prints variable a by using the System object at A (System@A), and then prints variable b at role B.

Roles are part of data types in Choral, adding a new dimension to typing. For example, the statement String@A a = "Hello from B"@A would be ill-typed, because the expression on the right returns data at a different role from that expected by the left-hand side.

From Choral to Java. Given class HelloRoles, the Choral compiler generates for each role parameter a Java class with the behaviour for that role, in compliance with the source class. Here, the Java class for role A is HelloRoles_A and the class for B is HelloRoles_B.

```java
public class HelloRoles_A {
    public static void sayHello() {
        String a = "Hello from A";
        System.out.println( a );
    }
}
```

```java
public class HelloRoles_B {
    public static void sayHello() {
        String b = "Hello from B";
        System.out.println( b );
    }
}
```
Each generated class contains only the instructions that pertain that role. If Java developers want to implement the behaviour of method `sayHello` for a specific role of the `HelloRoles` choreography, say A, they just need to invoke the generated `sayHello` method in the respective generated class (`HelloRoles_A`). If all Java programs interested in participating to `HelloRoles` do that, then their resulting global behaviour complies by construction with the source choreography.

**Distributed State.** Fields of Choral classes carry state and can be distributed over different roles. For example, a class `BiPair` can define a “distributed pair” storing two values at different roles.

```java
1 class BiPair<A, B><L @X, R @Y> {
2     private L @A left; private R @B right;

3     public BiPair(L @A left, R @B right) { this.left = left; this.right = right; }

4     public L @A left() { return this.left; }

5     public R @B right() { return this.right; } }
```

Class `BiPair` is distributed between roles A and B and has two fields, `left` and `right`. The class is also parameterised on two data types, L and R, which exemplifies our support for generics [Naftalin and Wadler 2007]. At line 1, `L @X` specifies that L is expected to be a data type parameterised over a single role, abstracted by `X`; similarly for `R @Y`. Choral interprets binders as in Java generics: the first appearance of a parameter is a binder, while subsequent appearances of the same parameter are bound. At line 2 we have the two fields, `left` and `right`, respectively located at `A` and `B` with types `L` and `R`, the constructor is at line 3, while accessors to the two fields are at lines 4–5.

Data structures like `BiPair` are useful when defining choreographies where the data at some role needs to correlate with data at another role, as with distributed authentication tokens. We apply them to a use case in Section 3.1.

### 2.2 Interaction

Choral programs become interesting when they contain interaction between roles—otherwise, they are simple interleavings of local independent behaviours by different roles, as in `HelloRoles`.

Choreography models typically come with some fixed primitives for interaction, e.g., sending a value from a role to another over a channel [Carbone et al. 2012]. Thanks to our data types parameterised over roles, Choral is more expressive: we can program these basic building blocks and then construct more complex interactions compositionally. This allows us to be specific about the requirements of choreographies regarding communications, leading to more reusable code. For instance, if a choreography needs only a directed channel, then our type system can see by subtyping that a bidirectional channel is also fine.

**Directed data channels.** We start our exploration of interaction in Choral from simple directed channels for transporting data. In Choral, such a channel is just an object (if you prefer, call it a choreography) that takes data from one place to another. We can specify this as an interface.

```java
interface DiDataChannel<A, B><T @X> { <S @Y extends T @Y> S @B com(S @A m); }
```

A `DiDataChannel` is the interface of a directed channel between two roles, abstracted by `A` and `B`, that can transfer data of type `T`. Method `com` takes any subtype of `T` located at `A`, `S @A`, and returns a value of type `S @B`. Parameterising data channels over the type of transferrable data (`T`) is important in practice for channel implementors, because they often need to deal with data marshalling. Choral comes with a standard library that offers implementations of our channel APIs for a few common types of channels, e.g., TCP/IP sockets supporting JSON objects and shared memory channels. Users can provide their own implementations.
Using a DiDataChannel, we can write a simple method that sends a string notification from a Client to a Server and logs the reception by printing on screen.

```java
notify(DiDataChannel<Client, Server<xString> ch, String@Client msg)
{ String@Server m = ch.com<String>(msg); System@Server.out.println(m); }
```

Note that String is a valid instantiation of T<@X of DiDataChannel because we lift all Java types as Choral types parameterised over a single role.

**Alien data types.** Compiling DiDataChannel to Java poses an important question: what should be the return type of method com in the code produced for role A? Since the return type does not mention A (we say that it is alien to A), a naïve answer to this question could be void, as follows.

```java
interface DiDataChannel_A<T> { <S extends T> void com(S m); }
```

It turns out that this solution does not work well with expressions that compose multiple method calls, including chaining like m1(e1,e2).m2(e3) and nesting like m1(m2(e)). As a concrete example, consider a simple round-trip communication from A to B and back.

```java
static <T@X> T@A roundTrip
{ (DiDataChannel@(A, B)<T> chAB, DiDataChannel@(B, A)<T> chBA, T@A mesg)
{ return chBA.com<T>(chAB.com<T>(mesg)); }
```

Method roundTrip takes two channels, chAB and chBA, which are directed channels respectively from A to B and from B to A. The method sends the input mesg from A to B and back by nested coms and returns the result at A.

A structure-preserving compilation of method roundTrip for role A would be as follows.

```java
static <T> T roundTrip
{ (DiDataChannel_A<T> chAB, DiDataChannel_B<T> chBA, T mesg)
{ return chBA.com<T>(chAB.com<T>(mesg)); }
```

Observe how the inner method call, chAB.com<T>(mesg), should return something, such that it can trigger the execution of the outer method call to receive the response. Therefore, the com method of DiDataChannel_A cannot have void as return type.

Programming language experts have probably guessed by now that the solution is to use unit values instead of void. Indeed, Choral defines a singleton type Unit, a final class that our compiler uses instead of void to obtain Java code whose structure resembles its Choral source code.

We now show the Java code produced by our compiler from DiDataChannel for both A and B.

```java
interface DiDataChannel_A<T> { <S extends T> Unit com(S m); }
```

```java
interface DiDataChannel_B<T> { <S extends T> S com(Unit m); }
```

Given these interfaces, the compilation of roundTrip for role A is well-typed and correct Java code. An alternative to using Unit would have been to give up on preserving structure in the compiled code; we chose in favour of our solution because preserving structure makes it easier to read and debug the compiled code (especially when comparing it to the source choreography), and also makes our compiler simpler.

The users of our compiled libraries are not forced to passing Unit arguments to methods, as for method com of DiDataChannel_B: for methods like these, our compiler provides corresponding “courtesy methods” that take no parameters and inject units automatically.
Bidirectional channels. An immediate generalisation of directed data channels brings us to bidirectional data channels, specified by `BiDataChannel`.

```java
interface BiDataChannel @ (A, B)<T, X, R> extends DiDataChannel @ (A, B)<T>, DiDataChannel @ (B, A)<R> { }
```

A `BiDataChannel` is parameterised over two types: `T` is the type of data that can be transferred from `A` to `B` and, vice versa, `R` is the type of data that can be transferred in the opposite direction. This is obtained by multiple type inheritance: `BiDataChannel` extends `DiDataChannel` in one and the other direction, which allows for using modularly a bidirectional data channel in code that has the weaker requirement of a directed data channel in one of the two supported directions. Distinguishing the two parameters `T` and `R` is useful for protocols that have different types for requests and responses, like HTTP. We discuss more types of channels (including symmetric channels) in Section 2.4.

Forward chaining. We use bidirectional channels to define a choreography for remote procedure calls, called `RemoteFunction`, which leverages the standard Java interface `Function<T, R>`.

```java
class RemoteFunction @ (Client, Server)<T, X, R> {
    private BiDataChannel @ (Client, Server)<T, R> ch;
    private Function @ Server<T, R> f;
    public RemoteFunction(BiDataChannel<T, R> ch, Function @ Server<T, R> f) {
        this.ch = ch; this.f = f; }
    public R @ Client call(T @ Client t) { return ch.<R>com(f.apply(ch.<T>com(t))); } }
```

In the experience that we gained by programming larger Choral programs (as those in Section 3), compositions of method invocations including data transfers as in line 5 of `RemoteFunction` are rather typical. In these chains, data transfers are read from right to left (innermost to outermost invocation), but most choreography models in the literature use a left-to-right notation (as in “Alice sends 5 to Bob”). To make Choral closer to that familiar choreographic notation, we borrow the forward chaining operator `>>` from F# [Petricek and Skeet 2009], so that `exp >> obj::method` is syntactic sugar for `obj.method(exp)`. For example, we can rewrite method `call` of `RemoteFunction` as follows, which is arguably more readable and recovers a more familiar choreographic notation.

```java
public R @ Client call(T @ Client t) { return t >> ch::<T>com >> f::apply >> ch::<R>com; }
```

### 2.3 Knowledge of choice

Knowledge of choice is a hallmark challenge of choreographies: when a choreography chooses between two alternative behaviours, roles should coordinate to ensure that they agree on which behaviour should be implemented [Castagna et al. 2011].

We exemplify the challenge with the following code, which implements the consumption of a stream of items from a producer `A` to a consumer `B`.

```java
// wrong implementation
consumeItems(DiDataChannel @ (A, B)<Item> ch, Iterator @ A<Item> it, Consumer @ B<Item> consumer) {
    if (it.hasNext()) {
        it.next() >> ch::<Item>com >> cons::accept; consumeItems(ch, it, consumer); }
}
```

Method `consumeItems` takes a channel from `A` to `B`, an iterator over a collection of items at `A`, and a consumer function for items at `B`. Role `B` works reactively, where its consumer function is invoked whenever the stream of `A` produces an element: if the iterator can provide an item (line 3), it is transmitted from `A` to `B`, consumed at `B`, and the method recurs to consume the other items (line 4).
The reader familiar with choreographies should recognize that this method implementation is wrong, due to (missing) knowledge of choice: the information on whether the if-branch should be entered or not is known only by A (since it evaluates the condition), so B does not know whether it should implement line 4 (receive, consume, and recur), or do nothing and terminate.

In choreographic programming, knowledge of choice is typically addressed by equipping the choreography language with a “selection” primitive to communicate constants drawn from a dedicated set of “labels” [Carbone and Montesi 2013; López et al. 2016]. This makes it possible for the compiler to build code that can react to choices made by other roles, inspired by a theoretical operator known as merging [Carbone et al. 2012]. In Choral, we adapt this practice to objects. Notably, Choral is expressive enough that we do not need to add a dedicated primitive, nor a dedicated set of labels.

We define a method-level annotation @SelectionMethod, which developers can apply only to methods that can transmit instances of enumerated types between roles (the compiler checks for this condition). For example, we can specify a directed channel for sending such enumerated values with the following DiSelectChannel interface.

```
interface DiSelectChannel<A, B> {
    @SelectionMethod <T extends Enum<T>> T select(T m);
}
```

Our compiler assumes that implementations of methods annotated with @SelectionMethod return at the receiver the same value given at the sender. (This is part of the contract for channels, and it is a standard assumption in implementations of choreographies.)

Typically, channels used in choreographies are assumed to support both data communications and selections. We can specify this with DiChannel (directed channel), a subtype of both DiDataChannel and DiSelectChannel.

```
interface DiChannel<A, B><T> extends DiDataChannel<A, B><T>, DiSelectChannel<A, B> {}
```

Using DiChannels, we can update consumeItems to respect knowledge of choice.

```
enum Choice<A> { GO, STOP }

consumeItems(DiChannel<A, B><Item<A> ch, Iterator<Item> it, Consumer<B<Item> consumer) {
    if (it.hasNext()) {
        ch.<Choice>select(Choice.GO);
        it.next() >> ch:<Item.com >> consumer::accept; consumeItems(ch, it, consumer);
    } else { ch.<Choice>select(Choice.STOP); }
}
```

Differently from the previous broken implementation of consumeItems, now role A sends a selection of either GO or STOP to B. Role B can now inspect the received enumerated value to infer whether it should execute the code for the if- or the else-branch of the conditional. This information is exploited by our static analyser to check that consumeItems respects knowledge of choice, and also by our compiler to generate code for B that reacts correctly to the choice performed by A. (A more extensive example containing also the code compiled for the receiver is given in Section 3.1.)

Our compiler supports three features to make knowledge of choice flexible. Firstly, our knowledge of choice check works with arbitrarily-nested conditionals. Secondly, knowledge of choice can be propagated transitively. Say that a role A makes a choice that determines that two other roles B and C should behave differently, and A informs B of the choice through a selection. Now either A or B can inform C with a selection, because our compiler sees that B now possesses knowledge of choice. Thirdly, knowledge of choice is required only when necessary: if A makes a choice and another role, say
B, does not need to know because it performs the same actions (e.g., receiving an integer from A) in both branches, then no selection is necessary. We explain the technicalities behind this in Section 4.

2.4 The family of Choral channels

Choral types give us a new way to specify requirements on channels that prior work implicitly assumed, leading to the definition of a family of channel interfaces diagrammed in Figure 3.

From the left-most column in Figure 3, at the top, we find DiDataChannel, representing a directed channel parameterised over T (the type of the data that can be sent). We obtain BiDataChannel, a bidirectional data channel, by extending DiDataChannel once for each direction: 1 it binds the role parameters of one extension in the same order given for the role parameters of BiDataChannel, giving us a direction from A to B and 2 it binds the role parameters of the other extension in the opposite way, giving us a direction from B to A. The result is that BiDataChannel defines two com methods: one transmitting from A to B, the other from B to A. The last lines in 1 and 2 in Figure 3 complete the picture: the first generic data type T binds data from A to B, second generic data type R binds data from B to A. The SymDataChannel in Figure 3, by extending the BiDataChannel interface and binding the two generic data types T and R with its only generic data type T, defines a bidirectional data channel that transmits one type of data, regardless its direction.

The right-most vertical hierarchy in Figure 3 represents channels supporting selections and it follows a structure similar to that of data channels. A DiSelectChannel is a directed selection channel and a SymSelectChannel is the bidirectional version—there is no BiSelectChannel since both directions exchange the same enumerated types.

The vertical hierarchy in the middle column of Figure 3 is the combination of the left-most and right-most columns. Interface DioChannel is a directed channel that supports both generic data communications and selections. BiChannel is its bidirectional extension (3 and 4 in Figure 3), and SymChannel is the symmetric extension of BiChannel.

3 USE CASES

We illustrate the expressiveness of Choral with a few more sophisticated use cases. We start with a protocol for distributed authentication in Section 3.1 and we compose it in a use case from the healthcare sector that mixes cloud computing, edge computing, and Internet of Things (IoT) (Section 3.2). For space reasons, we include as an addendum in Section 3.3 a use case on parallel computing (a distributed implementation of merge sort).
3.1 Distributed Authentication

We write a choreography for distributed authentication inspired by OpenID [OpenID Foundation 2014], where an IP ("Identity Provider") authenticates a Client that accesses a third-party Service.

We start by introducing an auxiliary class, AuthResult, that we will use to store the result of authentication. The idea is that, after performing the authentication protocol, both the Client and the Server should have an authentication token if the authentication succeeded, or an “empty” value if it failed. We model this by extending the BiPair class presented in Section 2.

```java
public class AuthResult<A, B>
    extends BiPair<A, B><Optional<A<AuthToken>>, Optional<B<AuthToken>> {
    public AuthResult(AuthToken<A> t1, AuthToken<B> t2) {
        super(Optional<A.<AuthToken>of(t1), Optional<B.<AuthToken>of(t2));
    }
    public AuthResult() {
        super(Optional<A.<AuthToken>empty(), Optional<B.<AuthToken>empty());
    }
}
```

The constructors of AuthResult guarantee that either both roles (A and B) have an optional containing a value or both optionals are empty (Optional is the standard Java type). Since AuthResult extends BiPair, these values are locally available by invoking the left and right methods.

We now present the choreography for distributed authentication, as the DistAuth class below.

```java
enum AuthBranch { OK, KO }
public class DistAuth<Client, Service, IP>{
    private TLSChannel<Client, IP><Object> ch_Client_IP;
    private TLSChannel<Service, IP><Object> ch_Service_IP;
    public DistAuth(
        TLSChannel<Client, IP><Object> ch_Client_IP,
        TLSChannel<Service, IP><Object> ch_Service_IP
    ) { this.ch_Client_IP = ch_Client_IP; this.ch_Service_IP = ch_Service_IP; }
    private static String calcHash(String salt, String pwd) { /*...*/ }
    public AuthResult<Client, Service> authenticate(Credentials credentials) {
        String salt = credentials.username >> ch_Client_IP::String<com >> ClientRegistry@IP::getSalt >> ch_Client_IP::String<com;
        Boolean valid = calcHash(salt, credentials.password) >> ch_Client_IP::String<com >> ClientRegistry@IP::check;
        if (valid) {
            ch_Client_IP.<EnumBoolean>select(AuthBranch@IP.OK);
            ch_Service_IP.<EnumBoolean>select(AuthBranch@IP.OK);
            AuthToken@IP t = AuthToken@IP.create();
            return new AuthResult<Client, Service>(ch_Client_IP.<AuthToken>com(t), ch_Service_IP.<AuthToken>com(t));
        } else {
            ch_Client_IP.<EnumBoolean>select(AuthBranch@IP.KO);
            ch_Service_IP.<EnumBoolean>select(AuthBranch@IP.KO);
            return new AuthResult<Client, Service>();
        }
    }
}
```

Class DistAuth is a multiparty protocol parameterised over three roles: Client, Service, and IP (for Identity Provider). It composes two channels as fields (lines 3–4), which respectively connect Client to IP and Service to IP—hence, interaction between Client and Service can only happen if coordinated by IP. The channels are of type TLSChannel, a class for secure channels.
from the Choral standard library that uses TLS for security and the Kryo library [Grotzke 2020] for marshalling and unmarshalling objects. Class TLSChannel implements interface SymChannel, from Section 2, so it can be used in both directions. The private method calcHash (omitted) implements the local code that Client uses to hash its password.

Method authenticate (lines 11–27) is the key piece of DistAuth, which implements the authentication protocol. It consists of three phases. In the first phase, lines 12–13, the Client communicates its username to IP, which IP uses to retrieve the corresponding salt in its local database ClientRegistry; the salt is then sent back to Client. The second phase (lines 14–15) deals with the resolution of the authentication challenge. Client computes its hash with the received salt and its locally-stored password, and sends this to IP. IP then checks whether the received hash is valid, storing this information in its local variable valid. The result of the check is a Boolean stored in the valid variable located at IP. The first two phases codify some best practices for distributed authentication and password storage [Grassi et al. 2017]: the identity provider IP never sees the password of the client, but only its attempts at solving the challenge (the salt), which Client can produce with private information (here, its password). In the third phase (lines 16–26), IP decides whether the authentication was successful or not by checking valid. In both cases IP informs the Client and the Service of its decision, using selections to distinguish between success (represented by OK) or failure (represented by KO). In the case of success, IP creates a new authentication token (line 19) and communicates the token to both Client and Service (inner calls to com at line 21). The protocol can now terminate and return a distributed pair (an AuthResult) that stores the same token at both Client and Service, which they can use later for further interactions (line 21). In case of failure, an authentication result with empty optionals is returned (line 25).

New to choreographic programming, DistAuth is a higher-order choreography: the channels that it composes are choreographies for secure communication that carry state—the result of the TLS handshake, which method com of TLSChannel uses internally. Taking this even further, we could overload method authenticate with a continuation passing style alternative that, instead or returning a result, takes as parameters choreographic continuations (objects that involve Client and Service) to be called respectively in case of success (line 20) or failure (line 25).

Compilation. We now discuss key parts of the compilation of DistAuth for role Client, i.e., the Java library that clients can use to authenticate to an identity provider and access a service.

```java
public class DistAuth_Client {
    private TLSChannel_A<Object> ch_Client_IP;
    public DistAuth_Client(TLSChannel_A <Object> ch_Client_IP)
    { this.ch_Client_IP = ch_Client_IP; }
    private String calcHash( String salt, String pwd ) { /*...*/ }

    public AuthResult_A authenticate(Credentials credentials) {
        String salt = ch_Client_IP.<String>com(ch_Client_IP.<String>com(credentials.username));
        ch_Client_IP.<String>com(calcHash(salt, credentials.password));
        switch(ch_Client_IP.<AuthBranch>select(Unit.id))
        { case OK ->
            { return new AuthResult_A( ch_Client_IP.<AuthToken>com(Unit.id), Unit.id); }
            case KO -> { return new AuthResult_A(); }
            default -> { throw new RuntimeException( /*...*/ ); } }
    }
}
```

The field, constructor, and static method at lines 2–4 are straightforward projections of the source class for role Client—fields and parameters pertaining only other roles disappeared. The
interesting code is at lines 7–15, which defines the local behaviour of Client in the authentication protocol. Note that forward chainings (\rightarrow) become plain nested calls in Java (lines 8 and 9). In line 8, the client sends its username to the identity provider and receives back the salt. Recall from Section 2 that the innermost invocation of method com returns a Unit, since the client acts as sender here. Once the username is sent, the innermost com returns and we run the outermost invocation of com, which received the salt through the channel with the identity provider. Line 9 sends the computed hash to the identity provider.

Line 10 exemplifies how our compiler implements knowledge of choice for roles that need to react to decisions made by other roles. The client receives an enumerated value of type AuthBranch, which can be either OK or KO, through the channel with the identity provider. Then, a switch statement matches the received value to decide whether (case OK) we shall receive an authentication token from the identity provider and store it as an AuthResult_A or (case KO) authentication failed.

3.2 A use case from healthcare: handling streams of sensitive vitals data

In this use case, we exemplify how developers can compose locally the libraries generated by independent choreographies, using a healthcare use case inspired by previous works on edge computing and pseudonimisation [Giallorenzo et al. 2019; Swaroop et al. 2019].

Suppose that a "healthcare service" in a hospital needs to gather sensitive data about vital signs (we call them vitals) from some IoT devices (e.g., smartwatches, heart monitors), and then upload them to the cloud for storage. This is a typical scenario that requires integration of libraries for participating in choreographies at the local level. We shall carry out the following two steps.

1. Define a new choreography class, called VitalsStreaming, that prescribes how data should be streamed from an IoT Device monitoring the vitals of a patient to a data Gatherer; this choreography will enforce that the Gatherer processes only data that is (a) correctly cryptographically signed by the device and (b) pseudonymised.
2. Implement the healthcare service a local Java class, called HealthCareService, that combines the Java library compiled from VitalsStreaming to gather data from the IoT devices with the Java library compiled from our previous DistAuth example to authenticate with the cloud storage service through a third-party service (this could be, e.g., a national authentication system) and upload the data.

Vitals choreography. VitalsStreaming implements the choreography for streaming vitals.
In lines 3–5, class VitalsStreaming composes a channel between the Device and the Gatherer and a Sensor object located at the Device (for obtaining the local vital readings). Line 6 defines a method that pseudonymises personal data in Vitals at the Gatherer. Likewise, line 7 is a method that the Gatherer uses to check that a message signature is valid. (We omit the bodies of these two static methods, which are standard local methods.) The interesting part of this class is method gather (lines 9–17). The Device checks whether its sensor is on (line 10) and informs the Gatherer of the result with appropriate selections for knowledge of choice (lines 11 and 16). If the sensor is on, then Device sends its next available reading to Gatherer (line 12). Gatherer now checks that the message is signed correctly (line 13); if so, it pseudonymises the content of the message and then hands it off to a local consumer function. Notice that Gatherer does not need to inform Device of its local choice, since it does not affect the code that Device needs to run. We then recursively invoke gather to process the next reading.

**Local code of the healthcare service.** The local implementation of the healthcare service acts as Gatherer in the VitalsStreaming choreography (to gather the data) and as the Client in the DistAuth choreography (to authenticate with the cloud storage). So we compose the compiled Java classes VitalsStreaming_Gatherer and DistAuth_Client, respectively.

```java
public class HealthCareService {
    public static void main() {
        TLSChannel_A toIP = HealthIdentityProvider.connect();
        TLSChannel_A toStorage = HealthDataStorage.connect();
        AuthResult_A authResult = new DistAuth_Client(toIP).authenticate(getCredentials());
        authResult.left().ifPresent( token -> {
            DeviceRegistry
                .parallelStream()
                .map(Device::connect)
                .map(VitalsStreaming_Gatherer::new)
                .forEach(vs -> vs.gather(data -> toStorage.com(new StorageMesg(token, data))));
        });
    }

    private static Credentials getCredentials() { /* ... */ }
}
```

The main method above idiomatically combines Java standard libraries with those generated by our compiler. In lines 3 and 4, we use auxiliary methods to connect to the identity provider (which implements IP in DistAuth) and the data storage service (which implements Service in DistAuth)—these services are provided by third parties, e.g., the national health system and some cloud provider. In line 5, we run distributed authentication as the Client. In line 6, we check if we successfully received an authentication token by inspecting the optional result. If so, in lines 7–10, we: obtain a parallel stream of Device objects from a local registry (lines 9–10); connect to each device in parallel, mapping devices to channels (line 9); and, in line 10, use each channel in a respective new instance of VitalsStreaming_Gatherer (the code compiled for Gatherer from VitalsStreaming). Finally, in line 11, we call the gather method to engage in the VitalsStreaming choreography with each device, passing a consumer function that sends the received data to the cloud storage service (including the authentication token).

Notice that we do not need to worry about pseudonymisation nor signature checking in the local code, since all these details are dealt with by the code compiled from VitalsStreaming.

### 3.3 Mergesort
The last use case that we present is a three-way concurrent implementation of merge sort [Knuth 1998], which exemplifies the design of parallel algorithms in Choral. Our implementation leverages role parameterisation such that participants collaboratively switch the roles that they play at runtime.

We represent the three concurrent parties as the roles A, B, and C. The idea is to follow the steps of standard merge sort, with A acting as "master" and the other as slaves. Specifically, A divides the unsorted list into two sublists and then communicates them to B and C, respectively. We then recursively invoke merge sort on each sublist, but with switched roles: in one call, B becomes the master that uses A and C as slaves; in the other call, C is the master using A and B as slaves. B and C then return their sorted sublists to A, which can merge them as usual.

The sequence diagram in Figure 4 represents the execution of our choreography by three endpoint nodes for an input list [15, 3, 14]. We use numbered subscripts to denote the round that each interaction belongs to. Node1 starts by playing role A and holds the initial list, while the other two nodes initially play the slave roles. In the first round, Node1 asks Node2 and Node3 to sort the sublists obtained from the initial list. This starts a recursive call (second round) where Node2 is the master and the others are slaves that help it to sort its sublist. Node2 now splits its sublist into smaller lists and asks the other two nodes to sort them (sort2). When this round is completed, each node contains a sorted sublist, and we can get up the recursion stack to the nodes playing their original roles, where now A collects the results from the others (B and C coordinate to decide who communicates first).

The logic that we have just described is implemented by the following Mergesort class.

```java
public class Mergesort(A, B, C) {
    SymChannel(A, B)<Object> ch_AB; SymChannel(B, C)<Object> ch_BC;
    SymChannel(C, A)<Object> ch_CA;

    public Mergesort()
        SymChannel(A, B)<Object> ch_AB, SymChannel(B, C)<Object> ch_BC,
        SymChannel(C, A)<Object> ch_CA
    ) { this.ch_AB = ch_AB; this.ch_BC = ch_BC; this.ch_CA = ch_CA; }

    public List<A<Integer>> sort(List<A<Integer>> a){
        if (a.size() > 1) {
            ch_AB.<Choice>select(Choice@A.L); ch_CA.<Choice>select(Choice@A.L);
            Mergesort(B, C, A) mb = new Mergesort(B, C, A)(ch_BC, ch_CA, ch_AB);
            Mergesort(C, A, B) mc = new Mergesort(C, A, B)(ch_CA, ch_AB, ch_BC);
            Double@A pivot = a.size() / 2@A >> Math@A::floor>> Double@A::valueOf;
            List<B<Integer> lhs = a.subList(0@A, pivot.intValue())
                ch_AB::<List<Integer>>com >> mb::sort;
            List<C<Integer> rhs = a.subList(pivot.intValue(), a.size())
                ch_CA::<List<Integer>>com >> mc::sort;
```
The sorting algorithm is implemented by the `sort` method, which uses the private `merge` method (omitted) to recursively handle the point-wise merging of ordered lists. For lists of size greater than 1, the algorithm creates two new `Mergesort` objects by instantiating roles such that they get switched as we discussed (lines 12–13), splits the list at the master, communicates the resulting sublists to the slaves (lines 16 and 18), recursively invokes merge sort with the switched roles (still lines 16 and 18), and finally merges the results (line 19).

The remaining code resembles (the choreography of) typical parallel merge sort implementations. A key benefit of Choral for parallel programming is that the compiled code is deadlock-free by construction, as usual for choreographic programming [Carbone and Montesi 2013].

4 IMPLEMENTATION

We discuss the main elements of the implementation of Choral. First, we show its syntax and comment on the main differences with Java’s. Then, we present the Choral type checker, including examples of the main errors related to roles that it detects and related error messages, and an overview of the type system we implemented. Finally, we describe the key components of the Choral compiler.

4.1 Language

Syntax. Figure 5 displays the grammar of Choral; dashed underlines denote optional terms and solid overlines denote sequences of terms of the same sort. We omit syntax for packages and imports, which is as in Java. The key syntactic novelties are underlined; they consist of i) syntax for declaring and instantiating role parameters and ii) the forward chaining operator `>` (cf. Section 2).

Role parameters have a separate namespace, and always appear in expressions like `@(A_1,...,A_n)` that follow the name of a class, interface, enum, or type parameter `e.g. DiChannel@(A,B)`. Also, they are introduced only by the declaration of a type (`e.g. class Foo@(A,B)` or a type parameter `e.g. <T@(A,B) extends Foo@(A,B) & Bar@(B,A)>`). Their scope is limited to the defining type, akin to type parameters in Java. The snippet below contains an example of shadowing of role parameters; for each use of `A`, we show its binding site with an arrow.

```
interface Foo@(A,B) extends Bar@(A,B) { <T@(A,B) extends Foo@(A,B) & Bar@(B,A)> T@(A,B) m();}
```

Type checker. The Choral type checker covers all common Java type errors (illegal type conversions, access to type members, etc.), as exemplified below.

```
Integer@A x = "foo"@A; // matching role, apply the same rules as Java
---------------------^ Compiler error

Incompatible types: expecting 'Integer@A' found 'String@A'.
```

When two or more roles are involved, programmers can make new errors that are pertinent to Choral. One type of such errors is that data types have incompatible roles.
As an example, consider the errors in Java, as exemplified by the (manual) projection below.

```java
void m (SymChannel<A,B<T>> x) {
  DiChannel<A,B<T> y = x; // ok, SymChannel<A,B<T> extends DiChannel<A,B<T>>
  SymChannel<B,A<T>> z = x; // not ok, mismatching roles
}
```

Cyclic inheritance is not allowed and the type checker does not discriminate over role parameters. As an example, consider the SymChannel interface: given its symmetric nature, one might try to force this equality by having \texttt{SymChannel@A,B} to subtype \texttt{SymChannel@B,A}.

```java
interface SymChannel@A,B<T,X> extends SymChannel@B,A<T> { /* ... */ }
```

Cyclic inheritance: 'SymChannel' cannot extend 'SymChannel'.

However, allowing declarations like the one above in Choral would result in cyclic inheritance errors in Java, as exemplified by the (manual) projection below.

```java
AN MD enum id {id}
```

Fig. 5. Syntax of the Choral language.
In many of the examples discussed so far, role parameters can be thought of as Java generics. Although this is a working approximation, some care is necessary in handling type instantiation due to some substantial differences between role parameters and type parameters: i) role parameters are never aliased and ii) subtypes cannot introduce or lose roles compared to their supertypes.

Role aliasing occurs by passing the same role as an argument to distinct formal role parameters.

Alas, this introduces security concerns (channels may have hidden bystanders) or complex communication semantics (what is the meaning of sending a `ReplicatedList<A,B>` over a channel expecting a `List<A>`?). These are general open problems for choreographies, left to future work.

Finally, the Choral type checker refines overload equivalence: it can discriminate overloaded methods by considering roles (e.g., `m(Char@B x)` and `m(Char@A x)` below). It also predicts potential clashes in the compiled Java code. Consider the following snippet and error message.

The last two signatures are distinguishable in Choral, since each method has different parameter types. However, this information is only available to role A, while the projection of both signatures at role B coincide. This is an instance of knowledge of choice but, differently from conditionals, it cannot be addressed locally (within the class/interface) because extending classes may introduce new branches and new points of choice by overriding and overloading, as in the example below.

Kinds and Types. Choral types can be intuitively thought of as “data types with role parameters”, and role parameters as a special kind of generic type parameters subject to additional usage restrictions—which we discussed discussed above. This points to a formalisation of roles as types for a new dedicated kind, written @. Under this interpretation, the declaration
defines \texttt{Integer} as a higher-kindred type constructor with parameter $A$ of kind $\alpha$. Applying \texttt{Integer} to role $B$ yields the fully constructed type denoted by \texttt{Integer@B}. Fully constructed types inhabit the
kind *. Following Moors et al. [2008] and Odersky et al. [2016], we refine * into subkinds by specifying an upper bound for their inhabitants and sacrifice the independence of kinds from types to simplify the handling of type parameters in generics. Kinds and types are given by the grammar below.

\[
\begin{align*}
\text{Kind} & ::= \alpha & \text{Kind of roles} \\
& | \ast \langle \text{Type} \rangle & \text{Kind of fully constructed subtypes of Type} \\
& | [X :: \text{Kind}] \Rightarrow \text{Kind} & \text{Kind of type constructors, } X \text{ binds in Kind} \\
\text{Type} & ::= X & \text{Type variable} \\
& | \text{Symbol} & \text{Type symbol, introduced by declarations of classes etc.} \\
& | [X :: \text{Kind}] \Rightarrow \text{Type} & \text{Type abstraction, binds } X \text{ in Kind and Type} \\
& | \text{Type} \llbracket \text{Type} \rrbracket & \text{Type concretion} \\
& | \& \langle \text{Type}, \ldots, \text{Type} \rangle & \text{Intersection type} \\
& | (\text{Type}) \Rightarrow \text{Type} & \text{Function type}
\end{align*}
\]

To ensure that type concretion respects kinds, we introduce a kinding system. A kinding judgement has the form $\Theta \vdash \text{Type} :: \text{Kind}$, which reads “type Type has kind Kind in $\Theta$”, where $\Theta$ is a finite mapping from type variables and symbols to kinds, written $X :: \text{Kind}$, called \textit{kinding environment}. Type abstraction and concretion are kinded by the following kinding rules.

\[
\begin{align*}
\Theta, X :: \text{Kind'} \vdash \text{Type} :: \text{Kind} & \quad \text{ABS} \\
\Theta \vdash [X] \Rightarrow \text{Type} :: [X :: \text{Kind'}] \Rightarrow \text{Kind} & \quad \text{APP} \\
\Theta, \text{Type} :: [X :: \text{Kind'}] \Rightarrow \text{Kind} \quad \Theta, X :: \text{Kind'} \vdash \text{Type'} :: \text{Kind'} \\
\Theta \vdash \text{Type} \llbracket \text{Type'} \rrbracket :: \text{Kind}
\end{align*}
\]

and are simplified by the reduction rule

\[
([X] \Rightarrow \text{Type})\llbracket \text{Type'} \rrbracket \rightarrow \text{Type}\llbracket \text{Type'}/X \rrbracket
\]

where $\{\text{Type'}/X\}$ denotes substitution of $X$ with $\text{Type'}$.

\textit{Typing}. Let $\Delta$ be a finite mapping from names of classes, interfaces, and parameters to type symbols and type variables. The type $(TE)A$ denoted by $TE$ in $\Delta$ is recursively defined as follows.

\[
(id\langle A \rangle \langle TE \rangle)A \triangleq (id)_A \llbracket (A)A \rrbracket \llbracket (TE)A \rrbracket \\
(id\langle TE \rangle)A \triangleq (id)_A \llbracket (TE)A \rrbracket \\
(id)_A \triangleq \Delta(id)
\]

A Choral type expression is well-formed in $\Delta$ and $\Theta$ whenever it denotes a type in $\Delta$ and this type is well-kindned in $\Theta$, i.e. whenever $\Theta \vdash (TE)A :: \text{Kind}$ for some kind Kind.

We use a bidirectional type system [Dunfield and Krishnaswami 2019; Pierce and Turner 2000] for statements and expressions. A type synthesis judgement has form $\Delta, \Gamma \vdash \_ :: \text{Term}$: \text{Type}, read “\text{Term} synthesises type \text{Type} in $\Delta$ and $\Gamma$”, where $\Gamma$ is a finite mapping from variable and parameter names to (fully instantiated) types—for conciseness, we omit the kinding environment $\Theta$ and assume all types are well-kindned. A type checking judgement has form $\Delta, \Gamma \vdash \_ :: \text{Term}$: \text{Type}, read “\text{Term} has type \text{Type} in $\Delta$ and $\Gamma$”. We present some representative derivation rules for these judgements.

Statements are checked against the expected return type to ensure that all exit points provide the correct type. For constructors and methods without explicit \texttt{return} statements the blank term \texttt{nil} constitutes an implicit return of any required type.

\[
\begin{align*}
\Delta; \Gamma \vdash \texttt{nil} :: \text{Type} & \quad \text{NIL} \\
\Delta; \Gamma \vdash \texttt{return Exp;} :: \text{Type} & \quad \text{RET}
\end{align*}
\]
Any other statement has a continuation and rules for checking their type check that the continuation is of the expected type as shown by the rule for assignments below.

\[
\frac{\Delta; \Gamma \vdash \text{Exp}: \text{Type}' \quad \Delta; \Gamma \vdash \text{Exp}': \text{Type}' \quad \Delta; \Gamma \vdash \text{Stm}: \text{Type}}{\Delta; \Gamma \vdash \text{Exp AsgOp Exp}'; \text{Stm}: \text{Type}} \quad \text{ASGOP}
\]

Observe that Type is provided by the derivation context and Type’ is inferred. No rule requires any "guessing" of types: they are either inferred or provided by the derivation context. For example, the rule below checks an expression against a type if it is possible to synthesise any of its subtypes.

\[
\frac{\Delta; \Gamma \vdash \text{Exp}: \text{Type}' \quad \text{Type}' <: \text{Type}}{\Delta; \Gamma \vdash \text{Exp}: \text{Type} \quad \text{<:}}
\]

This is the only rule without an associated term, but the change of direction guarantees against repeated applications in derivations. It is also the only one where the subtyping relation <: appears. Rule \text{minv} is for synthesising the type of method invocations in chained expressions.

\[
\frac{\Delta; \Gamma \vdash \text{Exp}: \text{S} \quad \Delta; \Gamma \vdash \text{Exp}: \text{T} \quad \text{mostSpecificMethod(S, m, (TE)}_{\Delta}, \bar{T}) = \text{U}}{\Delta; \Gamma \vdash \text{Exp}: (TE m(\text{Exp}') : \text{U}} \quad \text{MINV}
\]

The auxiliary function \text{mostSpecificMethod} yields the return type of the most specific method in \text{S} for the given name, actual type parameter, and types of arguments.

A judgment \(\Delta \vdash \text{Term}: \text{Ok in S}\) states that the \text{Term} is a correct implementation of a member of type \text{S}. Rule \text{m-ok} below is for checking the correct implementation of a method. The predicate \text{mtype}(\text{S, m, T}) holds whenever \text{T} is one of the types declared in type \text{S} for method \text{m}.

\[
\begin{align*}
\Delta' &= \Delta, \bar{T}: X_{\bar{T}}' \quad \text{mtype}(\text{S, m, [X_{\bar{T}} : [X_A : \tilde{A}]]} => *((\text{TE}_{\bar{T}})_{\Delta'}, \tilde{A}) : X_{\bar{T}}') \\
\Delta &\vdash \text{TE}_{\bar{T}} \text{ extends TE}_{\bar{T}} \quad \text{TE}_{\bar{T}} \text{ m(TE}_{\bar{T}} \text{ arg) Body: Ok in S} \quad \text{M-ok}
\end{align*}
\]

### 4.2 Compiler

Our compiler consists of a pipeline of three stages: parsing, type checking, and projection. Parsing is unsurprising, so we do not describe it here. Type checking operates as we have just discussed. Projection is the component that, given well-typed Choral code, produces a choreography-compliant Java library for each role.

We discuss the most important parts of projection, reporting its full formalisation in Appendix A. The projection of a Choral \text{class}, \text{interface}, or \text{enum} generates a corresponding Java term for each role parameter. If there are two or more roles, each Java artefact name is suffixed with the role that it implements, e.g. the Java class compiled from \text{class Foo(A, B)} for role \text{A} is called \text{Foo_A}. If the Choral class has exactly one role, then we use the same name, e.g. \text{class Integer@A} becomes \text{class Integer}. (This erases friction for the integration of Java types within Choral.)

Formally, projection is a (partial) function that, given a Choral term \text{Term} and the role \text{A} that we wish to generate the Java implementation of, returns a Java term, written \(\langle \text{Term} \rangle^A\). The projection \(\langle \text{TE} \rangle^A\) of a type expression \text{TE} at a role \text{A} is recursively defined below—we use the auxiliary function \text{roleName(id, i)} to retrieve the name of the \text{i}-th role parameter from the definition of \text{id}.

\[
\langle \text{id}@\bar{B} \rangle^A <\text{TE}> = \begin{cases} 
\text{id}<\langle \text{TE} \rangle^A > & \text{if } \bar{B} = \text{A} \\
\text{id}_{A'}^A <\langle \text{TE} \rangle^A > & \text{if } \text{A} \text{ is the i-th element of } \bar{B} \text{ and } \text{roleName(id, i)} = A' \\
\text{Unit} & \text{otherwise}
\end{cases}
\]
The projection \( \langle \text{Exp} \rangle^A \) of an expression \( \text{Exp} \) at role \( A \) is defined following a similar intuition: it is a recursive stripping of role information as long as \( A \) occurs in the type of \( \text{Exp} \) or any of its subterms (written \( A \in \text{rolesOf}(\text{Exp}) \)), otherwise it is the only instance of the singleton Unit (stored in its static field \( \text{id} \)), as illustrated by the cases of static field access and constructor invocation below.

\[
\langle \text{id}_\text{id}(B).f \rangle^A = \begin{cases} 
\langle \text{id}_\text{id}(B).f \rangle^A \cdot f & \text{if } A \in \text{rolesOf}(f) \\
\text{Unit}.\text{id} & \text{otherwise}
\end{cases}
\]

\[
\langle \text{new} (TE) \text{id}_\text{id}(B)(TE) \text{Exp} \rangle^A = \begin{cases} 
\text{new} \langle \langle TE \rangle \text{id}_\text{id}(B)(TE) \text{Exp} \rangle^A \langle \langle \text{Exp} \rangle^A \rangle & \text{if } A \in \overline{B} \\
\text{Unit}.\text{id}(\langle \langle \text{Exp} \rangle^A \rangle) & \text{otherwise}
\end{cases}
\]

The projection \( \langle \text{Stm} \rangle^A \) of a statement \( \text{Stm} \) at \( A \) is defined following the above intuition, save for the cases of conditionals and selections, which require care to address knowledge of choice (cf. Section 2.3). Specifically, the rule for projecting if statements: for the role evaluating the guard (read from its type), it preserves the conditional; for all other roles, the if disappears and it is replaced by the projection of the guard (since it might have side-effects) followed by the merging \( \sqcup \) of the projections of the bodies of the two branches and the projection of the continuation \( \text{Stm} \).

\[
\langle \text{if(Exp)}\{\text{Stm}_1\}\text{else}\{\text{Stm}_2\}\rangle^A = \begin{cases} 
\langle \langle \text{Exp} \rangle^A \rangle \langle \langle \text{Stm}_1 \rangle^A \rangle \text{else} \langle \langle \text{Stm}_2 \rangle^A \rangle \langle \langle \text{Stm} \rangle^A \rangle & \text{if } \text{Exp}: \text{boolean}@A \\
\langle \langle \text{Exp} \rangle^A \rangle \langle \langle \text{Stm}_1 \rangle^A \sqcup \langle \langle \text{Stm}_2 \rangle^A \rangle \rangle \langle \langle \text{Stm} \rangle^A \rangle & \text{otherwise}
\end{cases}
\]

The merge operator \( \text{Stm} \sqcup \text{Stm}' \) is a partial operator that tries to combine branching code [Carbone et al. 2012], which we adapt to Java for the first time. Essentially, given two Java terms, merging recursively requires them to be equivalent unless they are switch statements. Appendix A contains the full definition of merging. Here we report its most interesting case: merging switch statements.

\[
\begin{align*}
\text{switch}(\text{Exp})\{ \\
\text{case } \text{SwArg}_a \to \text{Stm}_a \\
\ldots \\
\text{case } \text{SwArg}_x \to \text{Stm}_x \\
\text{case } \text{SwArg}_y \to \text{Stm}_y \\
\} \text{Stm} = \\
\text{switch}(\text{Exp}')\{ \\
\text{case } \text{SwArg}_a \to \text{Stm}'_a \\
\ldots \\
\text{case } \text{SwArg}_x \to \text{Stm}'_x \\
\text{case } \text{SwArg}_z : \text{Stm}_z \\
\} \text{Stm}'
\end{align*}
\]

Above, the merging of two switch statements is a switch whose guard is the merging of the original guards (\( \text{Exp} \sqcup \text{Exp}' \)). Its cases consist of: for each case present in both the input switches (\( \text{SwArg}_a, \ldots, \text{SwArg}_x \)), we get a case in the result whose body merges the respective bodies of the original cases; all cases that are not shared, which are simply put in the result as they are (the lists of cases \( \text{case } \text{SwArg}_y \to \text{Stm}_y \) from the first and \( \text{case } \text{SwArg}_z : \text{Stm}_z \) from the second). An example of the result of merging was presented for DistAuth_Client in Section 3.1, where the cases for OK and K0 are combined from the respective projections for Client of the two branches in the source choreographic conditional evaluated by IP.

The rule for selections applies to statements of the form \( \text{Exp}; \text{Stm} \) if \( \text{Exp} \) calls (possibly in a chain call) a method annotated with \( @\text{SelectionMethod} \). (Our type checker checks that these annotations are used only for methods that take enumerated types as parameters, cf. Section 2.3.) For compactness, let \( S = \text{Exp}.(TE)\text{id}_1(\text{id}_2@A'.\text{id}_3) \) where \( @\text{SelectionMethod} \in \text{annotations}(\text{id}_1) \).

\[
\langle S; \text{Stm} \rangle^A = \begin{cases} 
\text{switch}(\langle S \rangle^A) \{ \\
\text{case } \text{id}_3 \to \{ \langle \text{Stm} \rangle^A \} \\
\text{default} \to \{ \text{throw new } \ldots \} \\
\langle S \rangle^A; \langle \text{Stm} \rangle^A \\
\end{cases}
\]

\text{if } S: \text{Enum}<\text{T}>@A \text{ for some } \text{T} \text{ otherwise}

For the recipient of the selection (first case), the statement becomes a switch on the projection of the Expression that will receive the selection, while the projection of the continuation Stm becomes the body of the corresponding case in the argument. The projection for the other roles (second case) is standard, projecting the Expression followed by the projection of the continuation Stm.

Our implementation of merging is smart enough to deal with some “uneffectful” usages of Unit. For instance, consider the merging below (right) that is required to project for role B.

```
if(Boolean.True@A){System@A.out.println("true"@A)}  ⇒  Unit.id(Unit.id)⊔nil
```

This is enabled by a unit-normalising operator, given in Appendix A.

5 TESTING

Testing implementations of choreographies is hard, since the distributed programs of all participants need to be integrated (integration testing). We introduce ChoralUnit, a testing tool that enables the writing of integration tests as simple unit tests for choreographic classes.

Following standard practice in object-oriented languages and inspired by JUnit, tests in ChoralUnit are defined as methods marked with a @Test annotation [Gamma and Beck 2006; Hamill 2004]. For example, we can define the following unit test for the VitalsStreaming class from Section 3.2.

```
public class VitalsStreamingTest@Device, Gatherer {  
	@Test  
	public static void test1(){  
		SymChannel@Device, Gatherer<Object> ch =  
		TestUtils@Device, Gatherer().newLocalChannel("VST_channel1"@Device, Gatherer);  
		new VitalsStreaming@Device, Gatherer(ch, new FakeSensor@Device())  
		.gather(new PseudoChecker@Gatherer()); } }  

class PseudoChecker@R implements Consumer@R<Vitals> {  
	public void accept(Vitals@R vitals) {  
		Assert@R.assertTrue("bad pseudonymisation"@R, isPseudonymised(vitals)); }  
	public void accept(Vitals@R vitals) {  
		Assert@R.assertTrue("bad pseudonymisation"@R, isPseudonymised(vitals)); }  
	private static Boolean isPseudonymised(Vitals vitals) { /* ... */ }  
}  
class FakeSensor@R implements Sensor@R { /* ... */ }
```

The test method test1 checks that data is pseudonymised correctly by VitalsStreaming. Test methods must be annotated with @Test, be static, have no parameters, and return no values.

In lines 4–5, we create a channel between the Device and the Gatherer by invoking the TestUtils.newLocalChannel method, which is provided by ChoralUnit as a library to simplify the creation of channels for testing purposes. This method returns an in-memory channel, which both Device and Gatherer will find by looking it up in a shared map under the key "VST_channel1". Thus, it is important that both roles will have the same key in their compiled code, which is guaranteed here by the fact that the expression "VST_channel1"@Device, Gatherer is actually syntax sugar for "VST_channel1"@Device, "VST_channel1"@Gatherer.

In line 6, we create an instance of VitalsStreaming (the choreography we want to test). We use a FakeSensor object to simulate a sensor that sends some data containing sensitive information (omitted). We then invoke the gather method, passing an implementation of a consumer that checks whether the data received by the Gatherer has been pseudonymised correctly.

Given a class like VitalsStreamingTest, ChoralUnit will compile it by invoking our compiler with a special flag (-annotate). This makes the compiler annotate each generated Java class with a @Choreography annotation that contains the name of its source Choral class and the role that the Java class implements. Once compilation is finished, the ChoralUnit tool can be invoked to run the tests in the VitalsStreamingTest class. This happens in three steps: (1) ChoralUnit finds all Java classes annotated with a @Choreography annotation whose name value corresponds to
VitalsStreamingTest. (2) Each discovered class has a method with the same name for each method in the source Choral test class (test 1 in our example). For each such method that is annotated with @Test, ChoralUnit starts a thread running the local implementation of the method by each class generated from the Choral source. (3) The previous step is repeated for all test methods.

In our example, VitalsStreamingTest is compiled to a class for Device and another for Gatherer, each with a test1 method. Thus, ChoralUnit starts two threads, one running test1 of the first generated Java class and the other running test1 of the second generated Java class.

6 FROM JAVA TO CHORAL, AND BACK

In this section, we illustrate how programmers can use Choral to transition existing sequential Java code to a concurrent version. Then, we provide a quantitative evaluation of how Choral impacts software development in terms of codebase size and compilation speed.

From Java to Choral. We illustrate how sequential Java code can be transformed into concurrent Choral code with an implementation of the algorithm for fast multiplication by Karatsuba and Ofman [1962], displayed in Figure 6 (left side). A possible distributed implementation in Choral is displayed on the right side of Figure 6. The differences are highlighted in yellow. The Choral implementation has three roles (A, B, and C), which distribute among themselves the three sub-calculations of the algorithm. The Choral implementation extends the original Java code with distribution information: we must specify where data is located (e.g., Long@A), the necessary communication channels (the three SymChannel parameters), add selections to ensure knowledge of choice (we omit the trivial declaration of the enum used in the selections), and add appropriate data transmissions. The Choral compiler assists the developer in writing these additions: given the Java code on the as input, the Choral compiler asks for all the aforementioned information.

Microbenchmarks. We now look at how Choral impacts software developments in more quantitative ways, in addition to the key benefit of choreography compliance. Specifically, we evaluate the performance of Choral’s compiler with microbenchmarks on 10 Choral programs. The results are shown in Table 1, which for each program reports (left to right): lines of code, number of roles, number of conditionals (if and switch blocks), lines of code of the compiled Java code (total for all roles), number of milliseconds to perform projection (Section 4.2). All code is well indented and the
Choreographies as Objects

| Program           | Choral (LOC) | # Roles | # Conditionals | Java (LOC) | Size Increase (%) | Projection (ms) |
|-------------------|--------------|---------|----------------|------------|-------------------|-----------------|
| HelloRoles        | 8            | 2       | 0              | 12         | 50%               | 0.398           |
| ConsumeItems      | 11           | 2       | 1              | 35         | 218%              | 0.222           |
| BuyerSellerShipper| 35           | 3       | 2              | 126        | 260%              | 1.619           |
| DistAuth          | 47           | 3       | 1              | 115        | 145%              | 1.053           |
| VitalsStreaming   | 38           | 2       | 1              | 71         | 87%               | 0.379           |
| MergeSort         | 62           | 3       | 4              | 231        | 273%              | 1.832           |
| QuickSort         | 63           | 3       | 3              | 199        | 216%              | 2.490           |
| Karatsuba         | 26           | 3       | 1              | 85         | 227%              | 1.388           |
| DistAuth5         | 57           | 5       | 1              | 197        | 246%              | 1.417           |
| DistAuth10        | 82           | 10      | 1              | 402        | 390%              | 2.791           |

Table 1. Performance results for the Choral compiler.

numbers exclude imports. We gather projection times on a machine equipped with an Intel Core i5-3570K 3.4 GHz CPU, 12 GB of RAM, running macOS 10.13 and Java 14. We focus on projection because it is the key novel phase in Choral; otherwise, our running times would be dominated by disk I/O. The reported times are averages of 1000 runs each, after a warm-up of 1000 prior runs.

Table 1 includes programs from this paper, plus three extra programs: BuyerSellerShipper is inspired by a recurring e-commerce example found in choreography articles [Carbone et al. 2012; Honda et al. 2016]; DistAuth5 and DistAuth10 are variants of the DistAuth class, where we respectively add 3 and 7 roles, 2 and 7 channels, and 4 and 14 selections for coordination.

Choral programs are much smaller than their compiled Java versions, which is good in itself—smaller codebases tend to host fewer bugs [Bessey et al. 2010]: compilation leads to an average increase of 206% in codebase size (going from the 50% for HelloRoles up to 390% for DistAuth10). The third and the fourth columns reveal a correlation between how much typing Choral saves programmers and two factors: the number of roles involved, which is explained by the fact that each Choral line of code involving some roles corresponds to a Java line of code for each role; and the number of conditionals, which typically require merging (Section 4.2)—this is visible in the comparison between MergeSort and QuickSort, where the former has 4 conditionals and an expansion of the 273% while the latter has 3 conditionals and an expansion of 216%.

Projection does not add any significant delay to the development experience: it averages ca. 1.35ms. This matches our own programming experience with Choral, where the compiler managed to feel quite responsive in providing quick feedback while coding. Projection is mostly influenced by the number of conditionals and roles, matching our previous observations.

Runtime performance is not included in Table 1, since performance is essentially indistinguishable from normal Java code. The Java code compiled from Choral resembles (choreography-compliant) manually-written code and its performance is essentially determined by the implementation of channels and other imported libraries, which can be chosen by the users.

7 RELATED WORK

Choral is a choreographic programming language: it makes the flow of interactions manifest from a global viewpoint, and the code generated from Choral implements exactly this flow [Montesi 2013].

The idea of synthesising local participant specifications that comply with choreographies has been a hot research topic for more than 20 years, and work in this line of research is typically based on automata or process calculi abstractions [Alur et al. 2000; Autili et al. 2018; Basu et al. 2012; Honda et al. 2016; Qiu et al. 2007]. Previous implementations of choreographic programming consist of Chor [Carbone and Montesi 2013] and AIoCJ [Dalla Preda et al. 2017], which are based on
process calculi and generate executable Jolie code. Compared to them, Choral solves the modularity problems mentioned in the Introduction, by revisiting choreographies under the light of mainstream abstractions. Another advantage is that the type of channels needed by a choreography is made explicit and can be user-defined, whereas previous work has fixed channel semantics (see, e.g., [Carbone et al. 2012; Carbone and Montesi 2013; Honda et al. 2016; Qiu et al. 2007]).

Our choreography-as-objects interpretation is inspired by the line of work on multitier programming [Cooper et al. 2006; Liu et al. 2009; Murphy VII et al. 2007, 2004; Neubauer and Thiemann 2005; Serrano et al. 2006; Weisenburger et al. 2018], where a distributed application is essentially defined as a single program that composes functions, each localised at a single participant. A function can then invoke special primitives to request remote computation by another participant, whose implementation must always be ready for such requests. Differently from choreographies, this makes the flow of communications implicit—indeed, multitier programming was not designed with the definition of choreographies as an aim. Choral generalises data types localised at a single participant to data types localised at many participants (roles). This enables our novel development process for choreography-compliant libraries; also, it unlocks for the first time higher-order composition of choreographies that carry state, generalising previous theories for choreographic procedures [Demangeon and Honda 2012]. The latest incarnation of multitier programming, ScalaLoci [Weisenburger et al. 2018], does not support higher-order composition of multitier programs: our new data types might thus be interesting also in that setting. Castro-Perez and Yoshida [2020] explored the parallelisation of a simple multitier first-order functional language, for which they can infer abstract (computation is not included) choreographies of the communication flows that these programs can enact; Choral could thus be used as an implementation language for such functions. Scalas et al. [2017] translate terms in a variant of security protocol notation (multiparty session types) to local specifications of communication behaviour in terms of process calculi, from which they generate Scala libraries. Their choreography language cannot include computation, so it cannot express any of our use cases. Also, the APIs of the libraries that they generate are very different from ours: they are direct representations of the communication behaviour that must be enacted and are meant to be used concatenatively, for example, o.send(..).receive(..).send(…). Choral brings two improvements over this approach. First, our APIs are more reusable: they change only if the source API is changed, not if the communication behaviour of a method is simply updated. Second, our generated APIs are more idiomatic: they are plain object APIs that look like the typical task-oriented APIs distributed by cloud vendors [Murty 2008; Wilder 2012], which makes Choral a candidate drop-in replacement for current development practices.

8 Conclusion

With the increased adoption of cloud computing, edge computing, the Internet of Things, and microservices, the need for libraries that implementors can use to participate correctly in choreographies is growing steadily [Atzori et al. 2010; Dragoni et al. 2017; Murty 2008; Wilder 2012]. Choral is a step towards equipping programmers with a tool that safely ferries them from the design of choreographies to compliant implementations at the press of the proverbial button.

In the future, Choral could also be a useful vector for the application of research on choreographies based on other paradigms (automata, processes, etc.): researchers could develop translations of their own choreography models to Choral, and then leverage our compiler to obtain library implementations that can be used in mainstream software (in Java). Hopefully, this will lead to more implementations of choreography theories, allowing for their evaluation [Ancona et al. 2016].

Discussion and Future work. Deniélo and Yoshida [2011] developed a theory for parametrising choreographies over “collections of roles” whose sizes are determined at runtime. All roles in the
same collection must be treated uniformly (e.g., broadcast). We can import that feature to Choral by introducing a similar kind of parameter for our data types. Another interesting future development might be to introduce support for the non-determinist selection of roles from collections, as recently suggested by Jongmans and Yoshida [2020], e.g., to define choreographies for work stealing.

For space reasons, we left some details of our programming experience with Choral to future presentations. We mention two aspects here: error handling and asynchronous programming.

Choral supports exception handling at a single role, which can then propagate errors to others via knowledge of choice. However, in our experience, it is more convenient to represent failures in return types, like we did in Section 3.1 by using \texttt{Optional}. The channel APIs that we showed in this paper are implemented by performing automatic retries. These APIs also have equivalent versions that wrap results in \texttt{Result} objects—essentially sum types of the transmitted value type and an error type, as in Go and Rust. Choosing among these implementations is up to the choreography programmer, and programmers might also devise channel implementations with their own strategies (e.g., exponential backoff with bound on the number of retries). Our compiler can, in principle, be extended to synthesise coordination for distributed exceptions, theorised by Carbone et al. [2008].

The choreographies that we presented here use channel APIs as if they were blocking. This does not mean that an endpoint must dedicate a thread for participating in a choreography: future versions of Java will include fibers and the asynchronous execution of blocking APIs (reactor pattern) [OpenJDK 2020]. Choral is compatible with this direction. Should programmers want to program a choreography explicitly for asynchronous execution by using continuation-passing style, this can be done by extending our channel APIs to take choreographic continuations as parameters.

REFERENCES

Rajeev Alur, Kousha Etessami, and Mihalis Yannakakis. 2000. Inference of message sequence charts. In Proceedings of the 22nd International Conference on on Software Engineering, ICSE 2000, Limerick Ireland, June 4-11, 2000, Carlo Ghezzi, Mehdi Jazayeri, and Alexander L. Wolf (Eds.). ACM, 304–313. https://doi.org/10.1145/337180.337215

Davide Ancona, Viviana Bono, Mario Bravetti, Joana Campos, Giuseppe Castagna, Pierre-Malo Deniëlou, Simon J. Gay, Nils Gesbert, Elena Giachino, Raymond Hu, Einar Broch Johnsen, Francisco Martins, Viviana Mascardi, Fabrizio Montesi, Rumyana Neykova, Nicholas Ng, Luca Padovani, Vasco T. Vasconcelos, and Nobuko Yoshida. 2016. Behavioral Types in Programming Languages. Foundations and Trends in Programming Languages 3, 2-3 (2016), 95–230.

Luigi Atzori, Antonio Iera, and Giacomo Morabito. 2010. The internet of things: A survey. Computer networks 54, 15 (2010), 2787–2805.

Marco Autilli, Paola Inverardi, and Massimo Tivoli. 2018. Choreography Realizability Enforcement through the Automatic Synthesis of Distributed Coordination Delegates. Sci. Comput. Program. 160 (2018), 3–29. https://doi.org/10.1016/j.scico.2017.10.010

Samik Basu, Tevfik Bultan, and Mereim Ouederni. 2012. Deciding choreography realizability. In Proceedings of the 39th ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages, POPL 2012, Philadelphia, Pennsylvania, USA, January 22-28, 2012, John Field and Michael Hicks (Eds.). ACM, 191–202. https://doi.org/10.1145/2103656.2103680

Al Bessey, Ken Block, Ben Chelf, Andy Chou, Bryan Fulton, Seth Hallem, Charles Henri-Gros, Asya Kamsky, Scott McPeak, and Dawson Engler. 2010. A few billion lines of code later: using static analysis to find bugs in the real world. Commun. ACM 53, 2 (2010), 66–75.

Marco Carbone, Kohei Honda, and Nobuko Yoshida. 2008. Structured Interactional Exceptions in Session Types. In CONCUR 2008 - Concurrency Theory, 19th International Conference, CONCUR 2008, Toronto, Canada, August 19-22, 2008. Proceedings (Lecture Notes in Computer Science), Franck van Breugel and Marsha Chechik (Eds.), Vol. 5201. Springer, 402–417. https://doi.org/10.1007/978-3-540-85361-9_32

Marco Carbone, Kohei Honda, and Nobuko Yoshida. 2012. Structured Communication-Centered Programming for Web Services. ACM Trans. Program. Lang. Syst. 34, 2 (2012), 8:1–8:78. https://doi.org/10.1145/2220365.2220367

Marco Carbone and Fabrizio Montesi. 2013. Deadlock-freedom-by-design: multiparty asynchronous global programming. In The 40th Annual ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages, POPL ’13, Rome, Italy - January 23 - 25, 2013, Roberto Giacobazzi and Radhia Cousot (Eds.). ACM, 263–274. https://doi.org/10.1145/2429069.2429101

Giuseppe Castagna, Mariangiola Dezani-Ciancaglini, and Luca Padovani. 2011. On global types and multi-party sessions. In Formal Techniques for Distributed Systems. Springer, 1–28.
David Castro-Perez and Nobuko Yoshida. 2020. Compiling first-order functions to session-typed parallel code. In *CC ’20: 29th International Conference on Compiler Construction*, San Diego, CA, USA, February 22-23, 2020, Louis-Noël Pouchet and Alexandra Jimboorean (Eds.). ACM, 143–154. https://doi.org/10.1145/3377555.3377889

Ezra Cooper, Sam Lindley, Philip Wadler, and Jeremy Yallop. 2006. Links: Web Programming Without Tiers. In *Formal Methods for Components and Objects*, 5th International Symposium, FMCO 2006, Amsterdam, The Netherlands, November 7-10, 2006, Revised Lectures (Lecture Notes in Computer Science), Frank S. de Boer, Marcello M. Bonsangue, Susanne Graf, and Willem P. de Roever (Eds.), Vol. 4709. Springer, 266–296. https://doi.org/10.1007/978-3-540-74792-5_12

Luís Cruz-Filipe and Fabrizio Montesi. 2016. Choreographies in Practice. In *Formal Techniques for Distributed Objects, Components, and Systems - 36th IFIP WG 6.1 International Conference, FORTE 2016, Held as Part of the 11th International Federated Conference on Distributed Computing Techniques, DisCoTec 2016, Heraklion, Crete, Greece, June 6-9, 2016, Proceedings (Lecture Notes in Computer Science)*, Elvira Albert and Ivan Lanese (Eds.), Vol. 9688. Springer, 114–123. https://doi.org/10.1007/978-3-319-39570-8_8

Mila Dalla Preda, Maurizio Gabbielli, Saverio Giallorenzo, Ivan Lanese, and Jacopo Mauro. 2017. Dynamic Choreographies: Theory And Implementation. *Logical Methods in Computer Science, 13, 2* (2017).

Romain Demangeon and Kohei Honda. 2012. Nested Protocols in Session Types. In *CONCUR 2012 - Concurrency Theory - 23rd International Conference, CONCUR 2012, Newcastle upon Tyne, UK, September 4-7, 2012. Proceedings (Lecture Notes in Computer Science)*, Maciej Koutny and Irek Ulidowski (Eds.), Vol. 7454. Springer, 272–286. https://doi.org/10.1007/978-3-642-32940-1_20

Pierre-Malo Deniélou and Nobuko Yoshida. 2011. Dynamic multimorphic session types. In *Proceedings of the 38th ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages, POPL 2011, Austin, TX, USA, January 26-28, 2011, Thomas Ball and Mooly Sagiv (Eds.). ACM, 435–446. https://doi.org/10.1145/1926385.1926435

Whitfield Diffie and Martin E. Hellman. 1976. New directions in cryptography. *IEEE Trans. Inf. Theory, 22, 6 (1976), 644–654. https://doi.org/10.1109/TIT.1976.1055638

Nicola Dragoni, Saverio Giallorenzo, Alberto Lluch-Lafuente, Manuel Mazzara, Fabrizio Montesi, Ruslan Mustafin, and Larisa Safina. 2017. Microservices: Yesterday, Today, and Tomorrow. In *Present and Ulterior Software Engineering*, Manuel Mazzara and Bertrand Meyer (Eds.). Springer, 195–216. https://doi.org/10.1007/978-3-319-67425-4_12

Joshua Dunfield and Neel Krishnaswami. 2019. Bidirectional Typing. *CoRR abs/1908.05839* (2019). arXiv:1908.05839 http://arxiv.org/abs/1908.05839

Erich Gamma and Kent Beck. 2006. JUnit. Saurer Giallorenzo, Fabrizio Montesi, and Marco Peressotti. 2019. Ephemeral Data Handling in Mi-

Paul Grassi, James L Fenton, EM Newton, RA Perlner, AR Regenscheid, WE Burr, JP Richer, NB Lefkovitz, JM Danker, Saverio Giallorenzo, Fabrizio Montesi, Ivan Lanese, and Jacopo Mauro. 2017. Dynamic Choreographies: Theory And Implementation. *Logical Methods in Computer Science, 13, 2* (2017).

Enrollment and Identity

Enrollment and Identity Proofing Requirements. url: https://pages.nist.gov/800-63-3/sp800-63a.html (2017).

Martin Grotzke. acc. May 2020. Kryo. https://github.com/EsotericSoftware/kryo.

Paul Hamill. 2004. *Unit test frameworks: tools for high-quality software development*. O'Reilly Media, Inc.

Sung-Shik Jongmans and Nobuko Yoshida. 2020. Exploring Type-Level Bisimilarity towards More Expressive Multiparty Session Types. In *Programming Languages and Systems - 29th European Symposium on Programming, ESOP 2020, Held as Part of the European Joint Conferences on Theory and Practice of Software, ETAPS 2020, Dublin, Ireland, April 25-30, 2020, Proceedings (Lecture Notes in Computer Science)*, Peter Müller (Ed.), Vol. 12075. Springer, 251–279. https://doi.org/10.1007/978-3-030-44914-8_10

Anatolii Alekseevich Karatsuba and Yu P Ofman. 1962. Multiplication of many-digital numbers by automatic computers. In *Doklady Akademii Nauk*, Vol. 145. Russian Academy of Sciences, 293–294.

Donald Knuth. 1998. Section 5.2. 4: Sorting by merging. *The Art of Computer Programming 3* (1998), 158–168.

Tanakorn Leesatapornwongsa, Jeffrey F. Lukman, Shan Lu, and Haryadi S. Gunawi. 2016. TaxDC: A Taxonomy of Non-Deterministic Concurrency Bugs in Datacenter Distributed Systems. In *Proc. of ASPLOS*, 517–530.

Jed Liu, Michael D. George, K. Vikram, Xin Qi, Lucas Waye, and Andrew C. Myers. 2009. Fabric: a platform for secure distributed computation and storage. In *Proceedings of the 22nd ACM Symposium on Operating Systems Principles 2009, SOSP 2009, Big Sky, Montana, USA, October 11-14, 2009*, Jeanna Neefe Matthews and Thomas E. Anderson (Eds.). ACM,
Choreographies as Objects

321–334. https://doi.org/10.1145/1629575.1629606
Alberto Lluch-Lafuente, Flemming Nielson, and Hanne Riis Nielson. 2015. Discretionary Information Flow Control for Interaction-Oriented Specifications. In Logic, Rewriting, and Concurrency (Lecture Notes in Computer Science), Vol. 9200. Springer, 427–450.
Hugo A. López and Kai Heussen. 2017. Choreographing cyber-physical distributed control systems for the energy sector. In SAC. ACM, 437–443.
Hugo A. López, Flemming Nielson, and Hanne Riis Nielson. 2016. Enforcing Availability in Failure-Aware Communicating Systems. In FORTE (Lecture Notes in Computer Science), Vol. 9688. Springer, 195–211.
Shan Lu, Soyeon Park, Eunsoo Seo, and Yuanyuan Zhou. 2008. Learning from mistakes: a comprehensive study on real world concurrency bug characteristics. In Proc. of ASPDAS. 329–339.
Fabrizio Montesi. 2013. Choreographic Programming. Ph.D. Thesis. IT University of Copenhagen. http://www.fabriziomontesi.com/files/choreographic_programming.pdf.
Adriaan Moors, Frank Piessens, and Martin Odersky. 2008. Generics of a higher kind. In Proceedings of the 23rd Annual ACM SIGPLAN Conference on Object-Oriented Programming, Systems, Languages, and Applications, OOPSLA 2008, October 19-23, 2008, Nashville, TN, USA, Gail E. Harris (Ed.). ACM, 423–438. https://doi.org/10.1145/1449764.1449798
Tom Murphy VII, Karl Crary, and Robert Harper. 2007. Type-Safe Distributed Programming with ML5. In Trustworthy Global Computing, Third Symposium, TGC 2007, Sophia-Antipolis, France, November 5-6, 2007, Revised Selected Papers (Lecture Notes in Computer Science), Gilles Barthe and Cédric Fournet (Eds.), Vol. 4912. Springer, 108–123. https://doi.org/10.1007/978-3-540-78663-4_9
Tom Murphy VII, Karl Crary, Robert Harper, and Frank Pfenning. 2004. A Symmetric Modal Lambda Calculus for Distributed Computing. In 19th IEEE Symposium on Logic in Computer Science (LICS 2004), 14-17 July 2004, Turku, Finland, Proceedings. IEEE Computer Society, 286–295. https://doi.org/10.1109/LICS.2004.1319623
James Murty. 2008. Programming amazon web services: S3, EC2, SQS, FPS, and SimpleDB. "O'Reilly Media, Inc.”
Maurice Nalfant and Philip Wadler. 2007. Java generics and collections. " O'Reilly Media, Inc.”
Matthias Neubauer and Peter Thiemann. 2005. From sequential programs to multi-tier applications by program transformation. In Proceedings of the 32nd ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages, POPL 2005, Long Beach, California, USA, January 12-14, 2005, Jens Palsberg and Martin Abadi (Eds.). ACM, 221–232. https://doi.org/10.1145/1040305.1040324
Object Management Group. 2011. Business Process Model and Notation. http://www.omg.org/spec/BPMN/2.0/.
Martin Odersky, Guillaume Martres, and Dmitry Petrashko. 2016. Implementing higher-kindred types in Dotty. In Proceedings of the 7th ACM SIGPLAN Symposium on Scala, SCALA@SPLASH 2016, Amsterdam, Netherlands, October 30 - November 4, 2016, Aggelos Biboudis, Manohar Jonnalagedda, Sandro Stucki, and Vlad Ureche (Eds.). ACM, 51–60. https://doi.org/10.1145/2998392.2998400
Peter W. O’Hearn. 2018. Experience Developing and Deploying Concurrency Analysis at Facebook. In Static Analysis - 25th International Symposium, SAS 2018, Freiburg, Germany, August 29-31, 2018, Proceedings (Lecture Notes in Computer Science), Andreas Podelski (Ed.), Vol. 11002. Springer, 56–70. https://doi.org/10.1007/978-3-319-99725-4_5
OpenID Foundation. 2014. OpenID Specification. https://openid.net/developers/specs/.
OpenJDK. acc. May 2020. Loom - Fibers, Continuations and Tail-Calls for the JVM. https://openjdk.java.net/projects/loom/.
Tomas Petricek and Jon Skeet. 2009. Real World Functional Programming: With Examples in F# and C. Manning Publications Co.
Benjamin C. Pierce and David N. Turner. 2000. Local type inference. ACM Trans. Program. Lang. Syst. 22, 1 (2000), 1–44. https://doi.org/10.1145/345099.345100
Zongyan Qiu, Xiangpeng Zhao, Chao Cai, and Hongli Yang. 2007. Towards the theoretical foundation of choreography. In WWW. IEEE Computer Society Press, United States, 973–982.
Alceste Scalas, Ornella Dardha, Raymond Hu, and Nobuko Yoshida. 2017. A Linear Decomposition of Multiparty Sessions for Safe Distributed Programming. In 31st European Conference on Object-Oriented Programming, ECOOP 2017, June 19-23, 2017, Barcelona, Spain (LIPIcs), Peter Müller (Ed.), Vol. 74. Schloss Dagstuhl - Leibniz-Zentrum für Informatik, 24:1–24:31. https://doi.org/10.4230/LIPIcs.ECOOP.2017.24
Manuel Serrano, Erick Gallesio, and Florian Loitsch. 2006. Hop: a language for programming the web 2.0. In Companion to the 21th Annual ACM SIGPLAN Conference on Object-Oriented Programming, Systems, Languages, and Applications, OOPSLA 2006, October 22-26, 2006, Portland, Oregon, USA, Peri L. Tarr and William R. Cook (Eds.). ACM, 975–985. https://doi.org/10.1145/1176617.1176756
Manu Sporny, Toby Inkster, Henry Story, Bruno Harbulot, and Reto Bachmann-Gmür. 2011. Webid 1.0: Web identification and discovery. W3C Editors Draft (2011).
K. Narendra Swaroop, Kavitha Chandu, Ramesh Gorrepatu, and Subimal Deb. 2019. A health monitoring system for vital signs using IoT. Internet of Things 5 (2019), 116 – 129. https://doi.org/10.1016/j.iot.2019.01.004
W3C. 2004. WS Choreography Description Language. http://www.w3.org/TR/ws-cdl-10/.
Pascal Weisenburger, Mirko Köhler, and Guido Salvaneschi. 2018. Distributed system development with ScalaLoci. *Proc. ACM Program. Lang.*, 2, OOPSLA (2018), 129:1–129:30. https://doi.org/10.1145/3276499

Bill Wilder. 2012. *Cloud architecture patterns: using microsoft azure*. "O’Reilly Media, Inc."
A PROJECTION TO JAVA

A.1 Projection

We omit modifiers (MD) and annotations (AN), they are rendered by the projection as they are.

\[
\text{(Enum) } \langle \text{enum id } \text{@ A} \{ \text{id} \} \rangle \rlap{=} \text{ enum id } \text{@ A } \{ \text{id} \}
\]

\[
\text{(Interface) } \langle \text{interface id } \text{@ A} \langle \text{FTP} \rangle \rangle \text{ extends } \text{TE } \& \text{ TE } \{ \text{MDef;} \} \rangle =
\]

\[
\text{interface name(id, A, A) } \{ \langle \text{FTP} \rangle \} \text{ extends } \{ \langle \text{TE} \rangle ^{\text{A}} \& \langle \text{TE} \rangle ^{\text{A}} \} \{ \langle \text{MDef} \rangle ^{\text{A}} \} \text{ } \{ \text{A } \in \text{ A} \}
\]

\[
\text{(Class) } \langle \text{class id } \text{@ A} \langle \text{FTP} \rangle \rangle \text{ extends } \text{TE } \& \text{ TE } \{ \text{CField} \& \text{CConst} \& \text{MDef} ; \text{ MDef } \{ \text{Stm} \} \} \rangle = \text{ class name(id, A, A) } \{ \langle \text{TE} \rangle ^{\text{A}} \& \text{ Stm } \{ \langle \text{TE} \rangle ^{\text{A}} \& \langle \text{TE} \rangle ^{\text{A}} \}
\]

\[
\{ \langle \text{CField} \rangle ^{\text{A}} \langle \text{CConst} \rangle ^{\text{A}} \langle \text{MDef} \rangle ^{\text{A}} \& \text{ MDef } \{ \langle \text{Stm} \rangle ^{\text{A}} \} \} \text{ } \{ \text{A } \in \text{ A} \}
\]

\[
\text{(FTP) } \langle \text{id } \text{@ A} \rangle \text{ extends } \text{TE } \& \text{ TE } = \begin{cases} \text{id } \text{@ A} \text{ extends } \{ \langle \text{TE} \rangle ^{\text{A}} \& \langle \text{TE} \rangle ^{\text{A}} \} \text{ } \{ \text{A } \in \text{ A} \} & \text{if } |\text{A}| \geq 1 \\ \text{id } \text{ extends } \{ \langle \text{TE} \rangle ^{\text{A}} \} & \text{otherwise} \end{cases}
\]

\[
\text{(TE) } \langle \text{void} \rangle ^{\text{A}} \text{ = void}
\]

\[
\langle \text{id } \text{@ } \text{A}(\text{B}) < \text{TE} > \rangle ^{\text{A}} = \begin{cases} \text{id } \langle \text{TE} \rangle ^{\text{A}} & \text{B } = \text{A} \\ \text{id } \text{@ } \text{A'} \text{ of } \text{TE} & \text{A } \text{ is the } i\text{-th element of } \text{B and roleName(id, i) } = \text{A'} \\ \text{Unit} & \text{otherwise} \end{cases}
\]

\[
\text{(MDef) } \langle \langle \text{FTP} \rangle \text{ TE id } \text{@ } \text{TE id} \rangle ^{\text{A}} = \langle \langle \text{FTP} \rangle \rangle \{ \langle \text{TE} \rangle ^{\text{A}} \text{ id } \{ \langle \text{TE id} \rangle ^{\text{A}} \}
\]

\[
\text{(CField) } \langle \text{TE id } \text{@ } \text{A} \rangle ^{\text{A}} = \begin{cases} \langle \text{TE} \rangle ^{\text{A}} \text{ id } & \text{if } \text{A } \text{ } \text{rolesOf(TE)} \\ \text{[blank]} & \text{otherwise} \end{cases}
\]

\[
\text{(CConst) } \langle \text{id } \text{@ } \text{A}(\text{TE id}) \text{(Stm)} \rangle ^{\text{A}} = \text{id } \text{@ } \text{A}(\text{TE id}) \text{[blank](Stm)}
\]

\[
\text{(Stm) } \langle \text{nil} \rangle ^{\text{A}} = \text{[blank]}
\]

\[
\text{(return Exp;)} ^{\text{A}} = \text{return } \langle \text{Exp} \rangle ^{\text{A}} ;
\]

\[
\text{switch} \{ \langle \text{Exp} \rangle ^{\text{A}} \} \text{ if } \text{typeOf(Exp) } < : \text{Enum} @ \text{A},
\]

\[
\text{case id } \text{-> } \{ \langle \text{Stm} \rangle ^{\text{A}} \}
\]

\[
\langle \text{Exp; Stm} \rangle ^{\text{A}} = \begin{cases} \langle \text{Exp} \rangle ^{\text{A}} ; \langle \text{Stm} \rangle ^{\text{A}} & \text{if } \text{A } \text{ rolesOf(Exp)} \\ \text{default->throw ...} & \text{ otherwise} \end{cases}
\]

\[
\langle \text{TE id=Exp; Stm} \rangle ^{\text{A}} = \begin{cases} \langle \text{TE} \rangle ^{\text{A}} = \langle \text{Exp} \rangle ^{\text{A}} ; \langle \text{Stm} \rangle ^{\text{A}} & \text{if } \text{A } \text{ rolesOf(TE)} \\ \langle \text{Exp} \rangle ^{\text{A}} ; \langle \text{Stm} \rangle ^{\text{A}} & \text{ if } \text{A } \text{ rolesOf(Exp) } \text{ rolesOf(TE)} \\ \langle \text{Stm} \rangle ^{\text{A}} & \text{ otherwise} \end{cases}
\]

\[
\langle \text{Exp } _1 \text{ AsgOp Exp } _2 \text{ Stm} \rangle ^{\text{A}} = \begin{cases} \langle \text{Exp} \rangle ^{\text{A}} \text{ AsgOp } \langle \text{Exp} \rangle ^{\text{A}} ; \langle \text{Stm} \rangle ^{\text{A}} & \text{if } \text{A } \text{ rolesOf(typeOf(Exp))} \\ \langle \text{Exp} \rangle ^{\text{A}} , \text{id} (\langle \text{Exp} \rangle ^{\text{A}} ) ; \langle \text{Stm} \rangle ^{\text{A}} & \text{ if } \text{A } \text{ rolesOf(Exp} _1 , \text{Exp} _2 ) \\ \langle \text{Stm} \rangle ^{\text{A}} & \text{ otherwise} \end{cases}
\]

\[
\langle \text{if(Exp)} \{ \text{Stm} _1 \} \text{else } \{ \text{Stm} _2 \} \rangle ^{\text{A}} =
\]
\[
\begin{align*}
\{\text{if}(\langle Exp \rangle^A)\{\langle Stm_1 \rangle^A\} & \text{ else } \{\langle Stm_2 \rangle^A\}\{\langle Stm \rangle^A\} \text{ if } \text{typeOf}(Exp) = \text{boolean}^A \} \\
& \{\langle Exp \rangle^A; \llbracket\{\langle Stm_1 \rangle^A\} \cup \llbracket\{\langle Stm_2 \rangle^A\}\rrbracket\} \{\langle Stm \rangle^A\} \text{ otherwise} \\
\{\langle Stm_1 \rangle^A\} & \{\langle Stm_2 \rangle^A\} \\
\{\text{switch}(Exp)\{\text{case } SwArg \rightarrow\{Stm\} \text{ default } \rightarrow\{Stm\}\}\{Stm\}^A = \\
& \text{switch}(\langle Exp \rangle^A)\{\text{case }\langle SwArg \rangle \rightarrow\{\langle Stm \rangle^A\} \text{ if } A \in \text{rolesOf}(\text{typeOf}(Exp)) \} \\
& \{\langle Exp \rangle^A; \llbracket\{\langle Stm \rangle^A\}\rrbracket\} \{\langle Stm' \rangle^A\} \text{ otherwise} \\
\{\text{try}\{Stm\}\text{catch}(TE id)\{Stm\}^A = \text{try}\{\langle Stm \rangle^A\}\llbracket\text{catch}(TE id)\{Stm\}\rrbracket^A \{Stm\}^A \\
\{\text{catch}(TE id)\{Stm\}^A = \{\text{catch}(\langle TE \rangle.id)\{\langle Stm \rangle^A\} \text{ if } A \in \text{rolesOf}(TE) \} \\
& \llbracket\text{blank}\rrbracket \text{ otherwise} \\
\langle Exp \rangle^A \{\text{lit} \}^A & = \begin{cases} \\
1 & \text{if } \text{lit} = \text{l@}(\emptyset) \text{ and } A \in \emptyset \\
\text{Unit.id} & \text{otherwise} \\
\end{cases} \\
\langle Exp BinOp Exp \rangle^A & = \\
\langle Exp Exp \rangle^A = \\
\langle \langle TE \rangle.id(\langle Exp \rangle) \rangle^A & = \begin{cases} \\
\llbracket\langle TE \rangle.id(\langle Exp \rangle)\rangle^A & \text{if } A \in \text{rolesOf}(\text{typeOf}(\langle TE \rangle.id(\langle Exp \rangle))) \\
\text{Unit.id}(\langle Exp \rangle^A) & \text{otherwise} \\
\end{cases} \\
\langle id\langle B \rangle.\langle TE \rangle.id(\langle Exp \rangle) \rangle^A & = \begin{cases} \\
\llbracket\langle id\langle B \rangle.\langle TE \rangle.id(\langle Exp \rangle)\rangle^A & A \in \emptyset \\
\text{Unit.id}(\langle Exp \rangle^A) & \text{otherwise} \\
\end{cases} \\
\langle \text{new } \langle TE \rangle.id(\langle TE \rangle(\langle Exp \rangle) \rangle^A & = \begin{cases} \\
\llbracket\text{new }\langle TE \rangle.id(\langle TE \rangle(\langle Exp \rangle)\rangle^A & A \in \emptyset \\
\text{Unit.id}(\langle Exp \rangle^A) & \text{otherwise} \\
\end{cases} \\
\langle FAcc \rangle^A \{\text{id} \}^A & = \begin{cases} \\
\text{id} & A \in \text{rolesOf}(id) \\
\text{Unit.id} & \text{otherwise} \\
\end{cases} \\
\langle id\langle B \rangle.f \}^A & = \begin{cases} \\
\llbracket\langle id\langle B \rangle.f \}^A \cdot f & A \in \text{rolesOf}(f) \\
\text{Unit.id} & \text{otherwise} \\
\end{cases} \\
\end{align*}
\]
A.2 Merging

\[ \overline{\text{Stm}} = \bigcup (\text{Stm}_1, \ldots, \text{Stm}_n) = [\text{Stm}_1] \sqcup \cdots \sqcup [\text{Stm}_n] \]

Statements

\[ \text{return } \text{Exp} \sqcup \text{return } \text{Exp}' = \text{return } \text{Exp} \sqcup \text{Exp}' \text{TE } \text{id} ; \text{Stm} \sqcup \text{TE } \text{id} ; \text{Stm}' = \text{TE } \text{id} ; (\text{Stm} \sqcup \text{Stm}') \]

\[ (\text{Exp}_1 \text{AsgOp} \text{Exp}_2 ; \text{Stm}) \sqcup (\text{Exp}'_1 \text{AsgOp} \text{Exp}'_2 ; \text{Stm}') \]

\[ = (\text{Exp}_1 \sqcup \text{Exp}'_1) \text{AsgOp} (\text{Exp}_2 \sqcup \text{Exp}'_2) ; (\text{Stm} \sqcup \text{Stm}') \]

\[ (\text{Exp} ; \text{Stm}) \sqcup (\text{Exp}' ; \text{Stm}') = (\text{Exp} \sqcup \text{Exp}') ; (\text{Stm} \sqcup \text{Stm}') \]

\[ \{\text{Stm}_1\} \text{Stm}_2 \sqcup \{\text{Stm}'_1\} \text{Stm}'_2 = \{\text{Stm}_1 \sqcup \text{Stm}'_1\} (\text{Stm}_2 \sqcup \text{Stm}'_2) \]

\[ \text{if}(\text{Exp})(\text{Stm}_1) \text{else}(\text{Stm}_2) \text{Stm} \sqcup \text{if}(\text{Exp}')(\text{Stm}'_1) \text{else}(\text{Stm}'_2) \text{Stm}' \\
\]

\[ = \text{if}(\text{Exp} \sqcup \text{Exp}')(\text{Stm}_1 \sqcup \text{Stm}'_1) \text{else}(\text{Stm}_2 \sqcup \text{Stm}'_2)(\text{Stm} \sqcup \text{Stm}') \]

\[ \text{switch } (\text{Exp}){ \\
\text{case } \text{id}_a : \text{Stm}_a ; \\
\text{...} \\
\text{case } \text{id}_x : \text{Stm}_x ; \\
\text{case } \text{id}_y : \text{Stm}_y } \}
\]

\[ = \text{switch } (\text{Exp} \sqcup \text{Exp}'){ \\
\text{case } \text{id}_a : \text{Stm}'_a ; \\
\text{...} \\
\text{case } \text{id}_x : \text{Stm}'_x ; \\
\text{case } \text{id}_y : \text{Stm}'_y } \}
\]

\[ \text{try } \{\text{Stm}_1\} \text{catch } (\text{TE } \text{id}) \{\text{Stm}_2\} \text{Stm}_3 \sqcup \text{try } \{\text{Stm}_1\} \text{catch } (\text{TE } \text{id}) \{\text{Stm}'\} \text{Stm}_4 \]

\[ = \text{try } \{\text{Stm}_1 \sqcup \text{Stm}_3\} \text{catch } (\text{TE } \text{id}) \{\text{Stm} \sqcup \text{Stm}'\} \text{Stm}_2 \sqcup \text{Stm}_4 \]

Statements

\[ \text{return } \text{Exp} \sqcup \text{return } \text{Exp}' = \text{return } \text{Exp} \sqcup \text{Exp}' \text{let } \bullet \in \{\text{null}, \text{this}, \text{id}\}, \bullet \sqcup \bullet = \bullet \]

\[ \text{let } \bullet \in \{\text{new } \text{id} (\text{TE}), \text{id} (\text{TE})\} , \bullet (\text{Exp}) \sqcup \bullet (\text{Exp}') = \bullet (\text{Exp} \sqcup \text{Exp}') \]

\[ (\text{Exp}_1 \text{BinOp} \text{Exp}_2) \sqcup (\text{Exp}'_1 \text{BinOp} \text{Exp}'_2) = (\text{Exp}_1 \sqcup \text{Exp}'_1) \text{BinOp} (\text{Exp}_2 \sqcup \text{Exp}'_2) \]

\[ \text{Exp}_1, \text{Exp}_2 \sqcup \text{Exp}_3, \text{Exp}_4 = (\text{Exp}_1 \sqcup \text{Exp}_3)(\text{Exp}_2 \sqcup \text{Exp}_4) \]

\[ .\text{id} \sqcup .\text{id} = .\text{id} \\
.\text{id}(\text{TE})(\text{Exp}) \sqcup .\text{id}(\text{TE})(\text{Exp}') = .\text{id}(\text{TE})(\text{Exp} \sqcup \text{Exp}') \]

\[ .\text{Exp}_1, \text{Exp}_2 \sqcup .\text{Exp}_3, \text{Exp}_4 = (.\text{Exp}_1 \sqcup .\text{Exp}_3)(.\text{Exp}_2 \sqcup .\text{Exp}_4) \]
A.3 Normaliser

Statements

\[
\begin{align*}
[\text{nil}] &= \text{nil} & [\text{return } \text{Exp};] &= \text{return } [\text{Exp}]; & [\text{TE id; } \text{Stm}] &= \text{TE id; } [\text{Stm}] \\
[\text{Exp AsgOp } \text{Exp'}; \text{Stm}] &= [\text{Exp}] \text{AsgOp } [\text{Exp'}]; [\text{Stm}] \\
[\{\text{Stm}\} \text{Stm}] &= \{[\text{Stm}]\} [\text{Stm}] \\
\text{NOOP}(\text{Exp}) &= \begin{cases} [\text{blank}] & \text{if } \text{Exp} \in \{\text{Unit.id, id id, this, null}\} \\
\text{Exp} & \text{otherwise} \\
\end{cases} \\
[\text{Exp; } \text{Stm}] &= \begin{cases} [\text{Stm}] & \text{if } \text{NOOP}([\text{Exp}]) = [\text{blank}] \\
[\text{Exp}; [\text{Stm}] & \text{otherwise} \\
\end{cases} \\
[\text{if(Exp)}\{\text{Stm}\}_\text{else}{}\{\text{Stm}_2\} \text{Stm}] &= \text{if}([\text{Exp}])\{[\text{Stm}]\}_\text{else}{}\{[\text{Stm}_2]\} [\text{Stm}] \\
[\text{switch}(\text{Exp})\{\text{case id } \rightarrow \{\text{Stm}\}_\text{default } \rightarrow \text{Stm'}\} \text{Stm}] &= \text{switch}([\text{Exp}])\{\text{case id } \rightarrow \{[\text{Stm}]\}_\text{default } \rightarrow \{\text{Stm'}\} [\text{Stm}] \\
[\text{try} \{\text{Stm}\} \text{catch (TE id)} \{\text{Stm}\} \text{Stm}] &= \text{try} \{[\text{Stm}]\} \text{catch (TE id)} \{[\text{Stm}]\} [\text{Stm}] \\
\end{align*}
\]

Expressions

\[
\begin{align*}
[\text{null}] &= \text{null} & [\text{null}]^* &= \langle \text{false}, \text{null} \rangle & [\text{this}] &= \text{this} & [\text{this}]^* &= \langle \text{false}, \text{this} \rangle \\
[\text{id}] &= \text{id} & [\text{id}]^* &= \langle \text{false}, \text{id} \rangle & \text{let } [\text{id}(\overline{\text{TE}})(\text{Exp})]^* &= \langle \circ, \circ \rangle, \text{ } [\text{id}(\overline{\text{TE}})(\text{Exp})] &= \circ \\
\text{let } [\text{Exp}]^* &= \langle \circ, \circ \rangle, \text{ } [\text{id}(\overline{\text{TE}})(\text{Exp})]^* &= \langle \bigvee, \text{id}(\overline{\text{TE}})(\circ) \rangle \\
\text{let } [\text{new id}(\overline{\text{TE}})(\text{Exp})]^* &= \langle \circ, \circ \rangle, \text{ } [\text{new id}(\overline{\text{TE}})(\text{Exp})] &= \circ \\
\text{let } [\text{Exp}]^* &= \langle \circ, \circ \rangle, \text{ } [\text{new id}(\overline{\text{TE}})(\text{Exp})]^* &= \langle \bigvee, \text{new id}(\overline{\text{TE}})(\circ) \rangle \\
[\text{Exp BinOp } \text{Exp'}] &= [\text{Exp}] \text{ BinOp } [\text{Exp'}] \\
\text{let } [\text{Exp}.\text{Exp'}]^* &= \langle \circ, \circ \rangle, \text{ } [\text{Exp}.\text{Exp'}] &= \begin{cases} \langle \circ \rangle & \text{if } \circ = \text{true} \\
\circ & \text{otherwise} \\
\end{cases} \\
\text{let } [\text{Exp}.\text{Exp'}] &= \langle \text{true, Unit.id} \rangle, \text{ } [\text{Exp}.\text{Exp'}] &= \begin{cases} \langle \text{true, Unit.id} \rangle & \text{if } \text{Exp}.\text{Exp'} = \text{Unit.id} \text{id}(\text{Exp}) \\
\langle \text{true, Exp} \rangle & \text{if } \text{Exp}.\text{Exp'} = \text{Unit.id} \text{id}(\text{Exp}) \\
\end{cases} \\
[\text{Exp}.\text{Exp'}]^* &= \begin{cases} \langle \text{false, Unit.id} \rangle & \text{if } \text{Exp} = \text{Unit} \text{ and } [\text{Exp}].[\text{Exp'}]^* = \langle \circ, [\text{null}] \rangle \\
\langle \circ \bigvee \circ, \circ \circ \rangle & \text{otherwise, let } [\text{Exp}]^* = \langle \circ, \circ \rangle \\
\text{and } [\text{Exp'}]^* = \langle \circ, \circ \rangle \\
\end{cases} \\
[.\text{id}]^* &= \langle \text{false}, \text{id} \rangle & \text{let } [\text{Exp}]^* &= \langle \circ, \circ \rangle, \text{ } [\text{id}.\text{Exp}]^* &= \langle \circ, \text{id} \circ \rangle \\
\text{let } [\text{Exp}]^* &= \langle \circ, \circ \rangle, \text{ } [\text{id}.\text{Exp}]^* &= \begin{cases} \langle \bigvee, \text{id}(\circ) \rangle & \text{if } \text{id} \neq \text{id} \\
\langle \text{true, [blank]} \rangle & \text{if } \text{NOOP}(\circ) = [\text{blank}] \\
\langle \bigvee, \text{null} \rangle \neq \text{id}(\circ) & \text{otherwise, let } \text{NOOP}(\circ) = \circ \\
\end{cases} \\
\text{let } [\text{id}(\overline{\text{TE}})(\text{Exp})]^* &= \langle \circ, \circ \rangle \text{ and } [\text{Exp}]^* &= \langle \circ, \circ \rangle, \text{ } [\text{id}(\overline{\text{TE}})(\text{Exp}).\text{Exp}]^* &= \langle \circ \bigvee \circ, \circ \circ \rangle \\
\end{align*}
\]