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Citation for published version:

Digital Object Identifier (DOI):
10.1145/2967973.2968595

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
18th International Symposium on Principles and Practice of Declarative Programming PPDP 2016

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Typechecking Protocols with Mungo and StMungo

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Abstract

We report on two tools which extend Java with support for static typechecking of communication protocols. Our Mungo tool extends Java with typestate definitions, which allow classes to be associated with state machines defining permitted sequences of method calls. A complementary tool, StMungo, takes a communication protocol specified in the Scribble protocol description language, and generates a typestate specification for each endpoint, capturing the permitted sequences of messages along that channel. Endpoint implementations can be validated by Mungo against their typestate definitions and then compiled as usual with javac. We formalise Mungo’s typestate inference system and demonstrate the Scribble, Mungo and StMungo toolchain via a typechecked SMTP client that can communicate with a real-world SMTP server.

1. Introduction

In this paper we present two tools which extend the Java development process with support for static typechecking of communication protocols. Mungo¹ extends Java with typestate definitions, which associate classes with state machines defining permitted sequences of method calls [42]. To associate a typestate definition with a class, the programmer adds a @Typestate annotation to the class telling Mungo where to find the typestate definition file. Mungo will then ensure that instances of the class are used in a manner consistent with the declared typestate.

StMungo (Scribble-to-Mungo) uses this typestate feature to connect Java to the broader setting of communication protocols specified in the Scribble protocol language [40]. Given a Scribble protocol projected to a particular endpoint (a so-called local protocol), StMungo will generate a typestate specification capturing the sequences of sends and receives permitted along that endpoint. Each endpoint implementation can be validated separately by Mungo against its typestate definition and then compiled as usual with javac.

The separate typechecking of each endpoint is integral to our approach, and is justified by the theory of multiparty session types [25], the formal foundation of Scribble. Multiparty session types provide an important safety guarantee: once each endpoint implementation is known to conform to its local protocol, the various implementations can be composed into a system free of communication errors.

Our work contributes to a line of research applying session types to real-world programming languages [9, 15–17, 22, 28, 32, 33, 35, 38]. In particular, our work builds on that of Gay et al. [23], which first connected session types to the object-oriented notion of typestate. They observed that the valid sequences of messages for a given endpoint could be captured by a typestate definition for a class, allowing the channel endpoint to be modelled as an object. While an important idea, this earlier work lacked a practical implementation and relied on typestate declaration on parameters and return types.

Mungo improves on this earlier work by employing an inference system, removing the need for typestate declarations on parameters and return types. The Mungo/StMungo toolchain offers other practical advances over previous efforts to combine session types with objects. For example, SJ [28] only supports binary session types, whereas StMungo generates Mungo specifications from multiparty session types. Furthermore, Mungo permits non-local use of objects with typestates. Using the @Typestate annotation means we avoid any need for language extensions.

Tracking object typestates requires a mechanism for managing object aliasing. For Mungo, we require objects which declare a typestate to be used linearly. While this is probably too restrictive for general-purpose programming, it is a standard technique for enabling typed communication along channels; most session type systems impose similar constraints on channel usage. Objects which lack typestate definitions can be used unrestrictedly alongside linear objects. In future work (§8) we will investigate more flexible alias control mechanisms, drawing on the substantial existing literature.

1.1 Contributions

The main contributions of the paper are as follows:

Mungo. We describe the Mungo typestate checker for Java. Mungo currently supports a subset of Java; support for the full language is discussed in §8.

StMungo. We describe StMungo (§3), which translates Scribble local protocols into Mungo typestate specifications. StMungo also generates Java method stubs for each endpoint.

SMTP case study. A substantial example, a statically typechecked SMTP client (§4), illustrates the end-to-end toolchain provided by Scribble, StMungo and Mungo.

Typestate inference system. We formalise the essential features of Mungo as a core object-oriented calculus (§5). We define a typestate inference system for that language and prove its type-safety (§6).

2. Mungo

Mungo² extends Java with an optional typestate system. The tool is implemented in Java using the JastAdd framework [24], a meta-

¹ Saint Mungo is the founder and patron saint of the city of Glasgow.

² The tool is maintained by the first author and can be downloaded from our web page [1].
We can now define a stack implementation Stack that conforms to the StackProtocol specification, using an integer array to store the elements. The annotation @Typestate("StackProtocol") is used to associate the typestate definition with the class:

```java
@Typestate("StackProtocol")
class Stack {
  private int[] stack; private int head;
  Stack() { stack = new int[MAX]; head = 0; }
  void push(int d) { stack[head++] = d; }
  int pop() { return stack[head--]; }
  Check isEmpty() {
    if(head == 0) return Check.EMPTY;
    return Check.NONEMPTY;
  }
  void deallocate() {}
}
```

Finally, having implemented StackProtocol, we can define a stack client that makes use of the Stack implementation, with Mungo verifying that Stack instances are used correctly.

```java
class StackUser {
  Stack pushN(Stack s, int n) {
    do { s.push(n--); } while(n>0); return s; }
  Stack popAll(Stack s) {
    Stack popAll (Stack s) pops all the elements of s.
    return s; }
  public static void main(String[] args) {
    StackUser su = new StackUser();
    Stack s = new Stack(); Stack s2;
    s = su.pushN(s,16); s2 = su.popAll(s);
    s = su.pushN(s,64); s = su.popAll(s);
    s.deallocate(); }
}
```

For illustrative purposes, the client defines two helper methods: pushN(Stack s, int n), for any n > 0, pushes the integers n, ..., 1 onto the stack s, and popAll(Stack s) pops all the elements of s.

Recursion and internal choice. Method pushN() illustrates the consumption of a recursive typestate offering a choice. The loop of the form do-while(exp) requires s to initially be either Empty or NonEmpty; at each iteration, the client decides (in the terminology of session types, it makes an internal choice) whether to push another element or exit, leaving the stack in the NonEmpty state. This is compatible with the recursive structure of the NonEmpty state, which permits an unbounded number of push() operations, looping back to NonEmpty each time.

Recursion and external choice. Method popAll(Stack s) also illustrates the consumption of a recursive typestate, but here the stack rather than the client makes the choice. (In session type terminology, the client offers an external choice.) This takes the form of a labelled do-while(true) in conjunction with a switch.

```java
s.deallocate();
```

We introduced Mungo through the example of a stack data structure which follows a typestate specification. Given the following enumerated type:

```java
enum Check { EMPTY, NONEMPTY }
```

then one possible typestate protocol for a stack is as follows:

```java
@Typestate("StackProtocol")
typestate StackProtocol {
  Empty = { void push(int): NonEmpty, 
    void deallocate(): end }
  NonEmpty = { void push(int): NonEmpty, 
    int pop(): Unknown }
  Unknown = { void push(int): NonEmpty, 
    Check isEmpty(): 
    <EMPTY: Empty, NONEMPTY: NonEmpty> }
}
```

This definition specifies that a stack is initially Empty. The Empty state declares two methods: push(int) pushes an integer onto the stack and proceeds to the NonEmpty state; deallocate() frees any resources used by the stack and terminates its usage. The deallocates() method is not available in any other state, requiring a client to empty the stack before it is done using it. In the NonEmpty state a client can either push() an element onto the stack and remain in the same state, or pop() an element from the stack and transition to Unknown.

Unlike push(), pop() must leave the stack in the Unknown state because the number of elements on the stack are not tracked by the protocol. From the Unknown state, one can either push() and proceed to NonEmpty, or call isEmpty() to explicitly test whether the stack is empty. Calling isEmpty() returns a member of the enumeration Check defined earlier. This idiom, based on Java enumerations, is the mechanism for communicating a choice made by the callee synchronously back to the client, and is explained in more detail below. Here, a stack implementation can choose between returning EMPTY and transitioning to Empty, or returning NONEMPTY and transitioning to NonEmpty.

Some Java features are not yet supported. Some we anticipate to be relatively straightforward extensions (synchronized statements, the conditional operator ?:, inner and anonymous classes, and static initialisers). Generics, inheritance and exceptions are non-trivial and are discussed in future work (§8). Currently, generics are not supported; inheritance is supported for classes without typestate definitions; and exceptions are supported syntactically but are typechecked under the (unsound) assumption that no exceptions are thrown. (A try-catch statement is typechecked by typechecking the try body; if an exception is thrown a typestate violation may result.)

Example 2.1. We introduce Mungo through the example of a stack data structure which follows a typestate specification. Given the following enumerated type:

```java
enum Check { EMPTY, NONEMPTY }
```

then one possible typestate protocol for a stack is as follows:

```
@Typestate("StackProtocol")
class Stack {
  private int[] stack; private int head;
  Stack() { stack = new int[MAX]; head = 0; }
  void push(int d) { stack[head++] = d; }
  int pop() { return stack[head--]; }
  Check isEmpty() {
    if(head == 0) return Check.EMPTY;
    return Check.NONEMPTY;
  }
  void deallocate() {}
}
```

Finally, having implemented StackProtocol, we can define a stack client that makes use of the Stack implementation, with Mungo verifying that Stack instances are used correctly.

```
class StackUser {
  Stack pushN(Stack s, int n) {
    do { s.push(n--); } while(n>0); return s; }
  Stack popAll(Stack s) {
    do { System.out.println(s.pop()); } while(!s.isEmpty());
    switch(s.isEmpty()) {
      case EMPTY: break loop;
      case NONEMPTY: continue loop;
    } while(true);
    return s; }
  public static void main(String[] args) {
    StackUser su = new StackUser();
    Stack s = new Stack(); Stack s2;
    s = su.pushN(s,16); s2 = su.popAll(s);
    s = su.pushN(s,64); s = su.popAll(s);
    s.deallocate(); }
}
```

For illustrative purposes, the client defines two helper methods: pushN(Stack s, int n), for any n > 0, pushes the integers n, ..., 1 onto the stack s, and popAll(Stack s) pops all the elements of s.

We now discuss some details of the programming model, drawing on this example where appropriate.

**Local variables, parameters, and return values.** The main() method above creates a single Stack instance, stores it in a local variable s, and then passes it to various invocations of pushN() and popAll(), from which it is also returned as a result. We also make use of the additional local variable s2. When returned from a method, the stack has a potentially different typestate than it did as an argument. No explicit typestate definitions are required for the parameter or return types of pushN() and popAll(), since Mungo can infer them.

An alternative to this “continuation-passing” style, using fields, is discussed below.

Recursion and internal choice. Method pushN() illustrates the consumption of a recursive typestate offering a choice. The loop of the form do-while(exp) requires s to initially be either Empty or NonEmpty; at each iteration, the client decides (in the terminology of session types, it makes an internal choice) whether to push another element or exit, leaving the stack in the NonEmpty state. This is compatible with the recursive structure of the NonEmpty state, which permits an unbounded number of push() operations, looping back to NonEmpty each time.

Recursion and external choice. Method popAll(Stack s) also illustrates the consumption of a recursive typestate, but here the stack rather than the client makes the choice. (In session type terminology, the client offers an external choice.) This takes the form of a labelled do-while(true) in conjunction with a switch.

The switch statement checks the stack contents returned by isEmpty(); in the NONEMPTY case, the loop continues, and in the EMPTY case the loop terminates. Due to their particular control flow, loops
of the form \texttt{label: do \{ switch \{ block \} while(true)\} are a suitable pattern for consuming a recursive typstate when the condition on the recursion is an external choice (i.e. based on an enumeration label).

**Linear objects.** Mungo ensures linear usage of objects that follow a typstate protocol; aliasing on objects allows for different method calls on an object that might lead to an inconsistent typstate. Notice that in line 15 of the \texttt{StackUser} example:

\begin{verbatim}
    s = su.pushN(s,16); s2 = su.popAll(s);
\end{verbatim}

the return value of \texttt{popAll()} is assigned to \texttt{s2}. Now, suppose line 16 were replaced with the following:

\begin{verbatim}
    s = su.pushN(s,64); s = su.popAll(s);
\end{verbatim}

In this case Mungo would report a linearity error on argument \texttt{s} in \texttt{su.pushN(s, 64)} informing the programmer that variable \texttt{s} is used uninitialised, because the usage of variable \texttt{s} in line 15 as an argument consumed its linear value.

**Inferring typstate for fields.** Using fields to store objects can lead to a more idiomatic object-oriented style than explicitly passing values between methods. To show how this works, we define a second client, \texttt{StackUser2}, that stores a \texttt{Stack} as a field.

\begin{verbatim}
1 class StackUser2 {
 2   private Stack s;
 3   StackUser2() { s = new Stack(); }
 4   boolean pushN(int n)
 5   { do { s.push(n--); }while(n>0); return true; }
 6   void finish() { s.deallocate(); }

7   public static void main(String[] args)
8   { loop : do {
9       System.out.println(s.pop());
10      switch(s.isEmptystate()) {
11         case EMPTY: break loop;
12         case NONEMPTY: continue loop;
13       } while(true); }
14   }
15   void finish() { s.deallocate(); }
16   StackUser2 su = new StackUser2();
17   if(su.pushN(15)||su.pushN(32))
18   { StackUser2 su2 = new StackUser2();
19       s = su.pushN(s,16); s2 = su.popAll(s);
20     }
21 }
\end{verbatim}

To track the typstate of a field we need to know the possible sequences in which methods of its containing class may be called. That, in turn, requires having a typstate for the containing class. In this case, to track the typstate of the field \texttt{s}, Mungo requires us to provide a typstate for \texttt{StackUser2}. This state machine will then drive typstate checking for those fields of \texttt{StackUser2} which have their own typstate definitions. For example we could define the following \texttt{StackUserProtocol} for \texttt{StackUser2}:

\begin{verbatim}
1   typestate StackUserProtocol {
2     Init = { boolean pushN(int): Cons,
3             void finish() : end}
4     Cons = { boolean pushN(int): Cons,
5              void popAll(): Init}
\end{verbatim}

Typechecking the field \texttt{s} of \texttt{StackUser2} field follows the possible sequences of method calls specified by \texttt{StackUserProtocol}, and also takes into account the constructor body of \texttt{StackUser2}. Then Mungo can guarantee that if a \texttt{StackUser2} instance is used according to \texttt{StackUserProtocol} then the \texttt{Stack} field of the object is also used according to \texttt{StackProtocol}.

**Short-circuit boolean expressions.** Line 16 above illustrates a final technical detail of typstate inference. The inference algorithm takes into account the fact that logical disjunction short-circuits if the first disjunct evaluates to \texttt{true}. Mungo will ensure that the typstate of \texttt{su} is consistent with there either being one, two or three successive invocations of \texttt{pushN()}.

### 3. StMungo: Scribble-to-Mungo

The integration of session types and typstate, defined by Gay et al. [23], consists of a formal translation of session types for communication channels into typstate specifications for channel objects. The main idea is that a channel object has methods for sending and receiving messages and the typstate specification defines the order in which these methods can be called; therefore it is a specification of the permitted sequences of messages, i.e. a channel protocol.

We extend this translation from binary to multiparty session types [25] and implement it as the StMungo (Scribble to Mungo) tool\(^3\), which translates Scribble [40, 45] local protocols into typstate specifications and skeleton-based implementation code. The resulting code is typechecked using Mungo. A Scribble local protocol describes the communication between one role and all the other participants in a multiparty scenario, including the way in which messages sent to different participants are interleaved. This interleaving is not captured by binary session types and by tools based on them, like SJ [28]. StMungo is based on the principle that each role in the multiparty communication can be abstracted as a Java class following the typstate corresponding to the role’s local protocol. The typstate specification generated from StMungo together with the Mungo typechecker can guide the user in the design and implementation of distributed multiparty communication-based programs with guarantees on communication safety and soundness. StMungo is the first tool to provide a practical embedding of Scribble multiparty protocols into object-oriented languages with typstate.

We illustrate StMungo on a multiparty protocol that models the process of booking flights through a university travel agent. The full details of this example are given in App. B. There are three participants involved: Researcher (abbreviated \texttt{R}), who intends to travel; Agent (\texttt{A}), who is able to make travel reservations; and Finance (\texttt{F}), who approves expenditure from the budget. After the request, quote and check messages requesting authorisation for a trip, Finance can choose to approve or refuse the request. The global protocol is defined as follows.

\begin{verbatim}
1 global protocol BuyTicket(role R, role A, role F){
2   request(Travel) from R to A;
3   quote(Price) from A to R;
4   check(Price) from R to F;
5   choice at F { approve(Code) from F to R,A;
6     ticket(String) from A to R;
7     invoice(Code) from A to F;
8     payment(Price) from F to A ; }
9   or { refuse(String) from F to R,A; }
\end{verbatim}

The Scribble tool is used to check the above protocol definition for well-formedness and to derive a local version of the protocol for each role, according to the multiparty session types theory [25]. This is known as \textit{endpoint projection}. Here we show the local protocol for Researcher, which describes only the messages involving that role. The \texttt{self} keyword indicates that \texttt{R} is the local endpoint.

\begin{verbatim}
1 local protocol BuyTicket_R(self R, role A, role F){
2   request(Travel) to A;
3   quote(Price) from A; check(Price) to F;
4   choice at F { approve(Code) from F;
5     ticket(String) from R ; }
6   or { refuse(String) from F; }
\end{verbatim}

Notice that the exchange of invoice and payment between Agent and Finance is not included. Similarly, the local projection for Agent omits the check message and the local projection for Finance omits

\(^3\)The tool is developed and maintained by the second author and can be downloaded from our web page [1].
the request, quote and ticket messages. StMungo converts the
BuyTicket_R local protocol into the RTProtocol typestate protocol:

```java
local protocol RTProtocol {
  1  typedef State0 {
  2  void send_requestTravelToA(Travel): State1
  3  State1={Price receive_quotePriceFromA(): State2}
  4  State2={void send_checkPriceToF(Price): State3}
  5  State3={{Choice1 receive_choice1LabelFromF():
  6    <APPROVE: State4, REFUSE: State6>
  7    State4={Code receive_approveCodeFromF(): State5}
  8    State5={String receive_ticketStringFromA(): end}
  9    State6={String receive_refuseTravelFromF(): end}
  10    rec Z1 {...
  11    _250(String) from S; ...
  12    continue Z1; }
  13    or { ...
  14    <_250DASH: State4, _250: State5>
  15    continue Z1; }
  16    or {
  17    subject(String) to S;
  18    continue Z3; }
  19    or {
  20    dataline(String) to S;
  21    continue Z3; }
  22    or{
  23    atad(String) to S;
  24    _250(String) from S;
  25    continue Z1; }
  26    } } ... }
}
```

StMungo translates the local protocol (SMTP_C) into a typestate
specification (CProtocol). In addition, it generates a skeletal
implementation based on sockets, although other implementations are possible.
Every interaction in the local protocol becomes a method call in
the typestate specification, as we will see shortly. State definitions
form groups into choices and impose sequencing.

Running the StMungo tool on SMTP_C produces the files
CProtocol.protocol, CRole.java and CMain.java.

1. CProtocol.protocol, captures the interactions local to the
   SMTP_C role as a typestate specification.
2. CRole.java, is a class that implements CProtocol by communica-
   tion over Java sockets. This is an API that can be used to
   implement the SMTP client endpoint.
3. CMain.java, is a skeletal implementation of the SMTP client
   endpoint. This runs as a Java process and provides a main()
   method which uses CRole to communicate with the other parties
   in the session, in this case the SMTP server.

The CProtocol generated by StMungo is defined in the following:

```java
local protocol SMTP_C(role S, self C) {
    _220(String) from S; ...
    rec X1 {
        choice at S {
            _250dash(String) from S; continue X1; }
        or {
            _250(String) from S; ...
            rec Z1 {
                ... data(String) to S; ...
                rec Z3 {
                    choice at C {
                        subject(String) to S;
                        continue Z3; }
                    or {
                        dataline(String) to S;
                        continue Z3; }
                    or {
                        atad(String) to S;
                        _250(String) from S;
                        continue Z1; }
                    } } ... }
    }
}
```

StMungo generates an API for this role, class RRole given in App. B,
which provides an implementation of RTProtocol. When instantiated,
it connects to the other role objects in the session (ARole and FRole).
The method calls, describing the messages exchanged with the other
roles, follow the interleaving specified by the RTProtocol typestate.
Alternatively, the developer may choose to ignore this API (and the
Mungo socket library that depends on), and use only the generated
typestate protocols to develop his/her own implementation. He/she
also has the ability to further refine the generated state machine,
e.g., give appropriate names to states, or use anonymous states to
have a coarser state refinement.

4. Case Study: Typechecking SMTP

In order to show the practicality and robustness of our StMungo
and Mungo toolchain, we have developed a substantial case study
in which we statically typecheck an SMTP client. We use this client
to communicate with the gmail server. The full source code of the
SMTP client can be found in [1].

SMTP (Simple Mail Transfer Protocol) is an internet standard
electronic mail transfer protocol, which typically runs over a TCP
(Transmission Control Protocol) connection. We consider the version
defined in RFC 5321 [41]. An SMTP interaction consists of an
exchange of text-based commands between the client and the server.
For example, the client sends the EHLO command to identify itself
and open the connection with the server. The commands MAIL FROM :
@address and RCPT TO : @address specify the e-mail address
of the sender and the receiver of the e-mail, respectively. The DATA
command allows the client to specify the text of the e-mail. The
QUIT command is used to terminate the session and close the
connection. The responses from the server have the following format:
three digits followed by an optional dash “-”, such as 250-, and then
some text, like OK. The server might reply to EHLO with 250 <text>
or to MAIL FROM or RCPT TO with 250 OK.

To typecheck the SMTP protocol using StMungo and Mungo, we
first represent the text-based commands as messages in a Scribble
global protocol, based on Hu’s work [27].

```java
global protocol SMTP(role S, role C) {
    // Global interaction between server and client.
    _220(String) from S to C;
    rec X1 {
        choice at S {
            _250dash(String) from S to C;
            continue X1; }
        or {
            250(String) from S to C; ... }
    } }
```

Then, we use the Scribble tool to validate and project the above
global protocol into local protocols, one for each role. We focus
only on the client side and describe in the following the SMTP_C
local protocol. This fragment of code of the SMTP describes a
loop (rec X1), in which the server S performs a choice between the
messages _250DASH and _250. Next, other loops follow (rec Z1 and
rec Z3), where in the second one the client C chooses among the
messages SUBJECT, to send the subject, DATALINE, to send a line of
text, or ATAD to terminate the e-mail by sending a dot.
The values of Choice1 are determined by the first interaction of every branch in the choice. The external choice itself is translated as a receive method returning the enumerated type Choice1 and given in lines 4-5 of CProtocol:

Choice1 receive_Choice1LabelFromS():
  <_250DASH; State4, _250; State5>

After choosing one of the branches, _250DASH or _250, the payload of type String is received via another method call, following the choice: receive_250DASHStringFromS() in line 7 and receive_250StringFromS() in line 8, respectively for the two available choices.

The internal choice made at self, namely role C (lines 11-17 of SMTP_C), is translated into a set of send methods, one for each branch of the choice (lines 12-14 of CProtocol). When running the program, only one of these methods will be called, thus performing a single message selection corresponding to it.

CRole implements all the methods in CProtocol. In this implementation, since communication occurs on Java sockets, we declare and create a new socket to connect to the gmail server. This is given in lines 2 and 4 in CRole, respectively.

@Typestate("CProtocol") class CRole {
  private Socket socketS = null; ...
  public CRole() {
    socketS = new Socket("smtp.gmail.com", 587);...}
  public static void main(String[] args) {
    CRole currentC = new CRole();
    ..._253;
    switch(/*label to be sent*/){
      case /*DATALINE*/:
        currentC.send_ATADToS();
        String _250msg =
        currentC.receive_250StringFromS();
        continue _251; }
    while(true); }

Typically the programmer would flesh out the skeletal implementation with extra logic that, for example, gets relevant input from the user or decides which choice to make when several are available, or customise CMain by adding SSL connection code for authentication with the gmail server. Mungo is able to statically check CMain, or any code that uses a CRole object, to ensure that methods of the protocol are called in a valid sequence and that all possible responses are handled. The programmer is not required to use the skeleton implementation of CMain, or even the CRole API. It is possible to

\[
D ::= \text{class } C : \{ F; M \} \mid \text{enum } E (\bar{t})
\]

\[
S ::= \bar{H} \mid \mu X.S \mid X
\]

\[
H ::= T m(T) : S \mid E m(T) : (S)_{i}E \in E
\]

\[
T ::= C \mid E \mid \text{bool} \mid \text{void}
\]

\[
F ::= T f
\]

\[
M ::= T m(T x) \{e\}
\]

\[
r ::= \text{this} \mid \text{r.f} \mid x
\]

\[
c ::= l \mid \text{tt} \mid \text{ff} \mid \text{null} \mid *
\]

\[
e ::= c \mid r \mid \text{r.m(e)} \mid r.f = e \mid e; e \mid r.f = \text{new } C
\]

\[
\lambda : e \mid \text{continue } \lambda
\]

\[
\text{switch (e) } \{ e_i \}_{i\in E} \mid \text{if (e) } e \text{ else } e
\]

Figure 1. Top-level syntax

write new code that uses the API, or to use the typestate specification to guide the development of an alternative API, or to refactor the typestate specification itself.

5. A Core Calculus for Mungo

In this section we define the syntax and operational semantics of a core object-oriented calculus, based on [23] and used to formalise Mungo. Note that we only formalise the inference system and not the ability of Mungo to work with full Java, as this would require formalising a large subset of Java.

Syntax. The syntax of the calculus is given in Fig. 1. We use \( \tilde{e} \) to denote a possibly empty set of elements that range over the subject meta-variable. A program is a set of type declarations \( \bar{D} \), each of which declares either a class or an enumerated type. A class declaration defines a class named \( C \) with typestate specification \( S \), fields \( F \) and methods \( M \). An enumeration declaration defines an enumerated type named \( E \) with a non-empty set of \( \bar{f} \) of enum values. For simplicity, our language has no support for inheritance or interfaces. We assume that a program has unique names for classes and enumerations, and a class has unique names for fields and methods.

The formal treatment assumes as an implicit context a program \( \bar{D} \), which can be accessed by the following functions: given that class \( C : \{ F; M \} \in \bar{D} \) we define fields(\( C \)) = \( F \), methods(\( C \)) = \( M \), typestate(\( C \)) = \( S \); and enums(\( E \)) = \( \bar{f} \) if enum \( E \). (\( \bar{t} \)) \in \bar{D} is a typestate definition \( S \) specifies a state machine that has as actions the methods of a class. A typestate definition is either an internal choice \( \bar{H} \) of method signatures, or a recursive typestate \( \mu X.S \), which may contain the recursive typestate variable \( X \). A method signature \( H \) can have two forms, depending on whether the method transitions to a state \( S \), or it is an external choice \( E m(T) : (S)_{i}E \in E \) to a state \( (S)_{i}E \); in the latter case the return type of the method must be \( E \). The empty or inactive typestate \( [] \) can also be written end. Well-formedness conditions ensure that state \( \mu X.X \) is not well-formed and that all state definitions are closed. A type is either the name of a class or enumeration, void or bool. A field declaration is a field name \( f \) associated with a type \( T \). A method declaration \( T m(T x) \{e\} \) specifies a return type \( T \), the name \( m \) of the method, the type \( T \) of the parameter \( x \), and the expression \( e \) which comprises the method body. A path is either the atomic path this denoting the current object (receiver), the composite path \( r.f \) denoting the field \( f \) of the object denoted by \( r \), or a parameter \( x \). At runtime paths are resolved to heap locations (see runtime syntax below). A constant is the special value null which is assignable to any class type, a bool or void literal, or an enum value \( i \). A constant or a path is an expression. In the expression forms method call \( r.m(e) \), field assignment \( r.f = e \), and object creation \( r.f = \text{new } C \), have the target object of the invocation or assignment is restricted to a path
which jump to the enclosing expression labelled by \( \lambda \)
expression, labelled expressions \( \lambda : e \), and continue expressions
which jump to the enclosing expression labelled by \( \lambda \).

**Configurations and runtime syntax.** Fig. 2 extends the source
syntax with additional runtime constructs used by the operational
semantics. A configuration \( h, e \) is the pair of a heap \( h \) and runtime
expression \( e \). The heap \( h \) is defined as an object \( C : o \), where \( C \)
is the class of the object and \( f : o \) are its fields; the contents of each
field is either a constant \( c \) or another object. The “heap” is a
tree of objects, with neither cycles nor sharing, due to the linearity
of object references enforced by the type system (see §6).

The expression \( e \) in a configuration \( h, e \) is a runtime expression
in which every (compile-time) path of the form this. \( r. f \) or \( x. h \)
has been replaced by a runtime path which refers to a heap value.
A runtime path \( r. f \) in a heap \( h \) is either the object path root denoting \( h \)
itself or the composite path \( r. f \) denoting the field \( f \) of the object
denoted by \( r \), where \( r \) is also a path in \( h \). Runtime expressions
also include the form \( e @ r \), which is an expression \( e \) which has been
tagged with \( @ r \) to track the active receiver. A value \( v \) is either a
constant \( c \) or runtime path \( r \). Every runtime expression is either a
value, or uniquely of the form \( e[x] \), where \( e \) is an evaluation context
(an expression with a hole). As usual, the notation \( e[x] \) denotes the
plugging of the hole in \( e \) with an expression \( x \).

The operational semantics is annotated with labels \( l \) that denote
the creation of a new object \( r. f. new C \), an enum value choice \( r(l) \),
method call \( r. f. m T \), assigning a field \( r. f = v \), the conditional
label \( (\ell f) \), and the silent label \( (\ell) \). The definition of states is extended
to the set of enum values \( (l \mid \ell f)_E \) and we define action labels \( s \)
for labels: internal choice \( C m T \), external choice \( E m T \): \( l \), and for
enum values \( l \).

**Labelled reduction semantics.** We define heap access and
update functions that are used by the reduction relation in Fig. 3:
\( h(\text{root}) = h \), \( h[r. f] = o \) and \( h[r. f \rightarrow o'] = h[r \rightarrow C[f : o, f : o']] \) if
\( h[r] = C[f : o, f : o] \). The root object is accessed via \( h(\text{root}) \).
The access of a field \( h[r. f] \) is inductively defined on the access of \( h(r) \).
Similarly, we use the heap access function to update object fields
as in \( h[r, f \rightarrow o] \). Fig. 3 defines the labelled reduction semantics;
hereafter by “expression” we shall mean runtime expression, and
by “path” runtime path, unless otherwise indicated. Rule \( R-\text{Seq} \)
discards the value \( v \) in a \( \tau \) label and proceeds with the evaluation
of \( e \). Rules \( R-\text{True} \) and \( R-\text{False} \) are the usual rules for the \( \text{if} \) 
...else expression and are annotated with label \( i f \). Rule \( R-\text{New} \) is labelled
with \( r. f. new C \) and overwrites the contents of the field \( r. f \) by a new
object \( C[f : \text{init}(T)] \) whose fields are all initialised to the value
\( \text{init}(T) \), where \( T \) is the type of the field, defined as:
\( \text{init}(C) = \text{null} \); \( \text{init}(E) = E_{\text{eq}} \); \( \text{init}(\text{bool}) = \text{false} \);
and \( \text{init}(\text{void}) = \text{null} \), where for every enumerated type \( E \) we require there to be a distinguished element
\( E_{\text{eq}} \) in \( \text{enum}(E) \). The result of \( R-\text{New} \) is the \text{void} value \( \ast \). There
is no allocation of a fresh location; instead the object is constructed at
an existing location \( r. f \). There are two assignment rules, depending
on whether the value being assigned is a constant or an object path.
Both forms return the \text{void} value \( \ast \). A constant \( c \) has no associated
typestate and may be used unrestrictedly; therefore the \( \text{R-Asgn}C \) rule
is labelled with \( \tau \) and simply updates the heap to store \( c \) in \( r. f \). A path

\[
\begin{align*}
on & ::= C[\overline{f} : o] \mid c & r & ::= \text{root} \mid r.f \\
e & ::= \ldots \mid e @ r & v & ::= c \mid r \\
S & ::= \ldots \mid (S)_{E \mathcal{R}} \quad s & ::= T m(T) \mid E m(T): l \mid l \\
E & ::= [ ] \mid r.m(E) \mid r.f = E \mid E \cdot e \mid \text{switch}(E) \{e\}_{E \mathcal{R}} \mid E @ r \mid \text{if}(E) e \text{else } e \\
\ell & ::= r.f.\text{new} C \mid r.(l) \mid r.T m T' \mid r.f = v \mid \tau \mid \text{if} \\
\end{align*}
\]

**Figure 2. Runtime syntax**

\( r \), rather than an arbitrary expression. The other expression forms
include sequential composition \( e; e' \), switch expressions, \( \text{if} \) ...else
expression, labelled expressions \( \lambda : e \), and continue expressions
which jump to the enclosing expression labelled by \( \lambda \).

6. **Typtypestate Inference**

In this section we formalise a typestate inference system and prove
its safety properties. The system presented here infers a typestate
The syntax of the inferred types, ranged over by \( \Delta \), is a preorder. The typestate imposes an order of pairs of typestates using rules \( S-Rec1 \) and \( S-Rec2 \). The typestate inference rules for expressions are given in Fig. 6.

**Definition 6.2** (Transition on typestates). Transition relation \( S \xrightarrow{t} S' \) is defined as:

\[
T m(T) : S \xrightarrow{\tau \text{ r}(T)} S \quad \quad \quad \ell' \in \text{enums}(E) \quad E m(T) : (S)_{r(E)} \xrightarrow{E \text{ m\text{r}f}} S' \\
H \xrightarrow{\tau} H' \quad H' \xrightarrow{\tau} S \quad \mu X S / X \xrightarrow{\tau} S' \quad \ell' \in \text{enums}(E) \quad (S)_{r(E)} \xrightarrow{\tau} S' 
\]

The first two rules state that a method prefixed typestate reduces to its continuation under a label denoting the prefix method signature itself. The next two rules state that reduction can occur in a set of typestates and under recursion, respectively. The last rule defines a reduction on a runtime typestate, as defined in Fig. 2. It states that a branching typestate reduces to one of its components by using the corresponding enumerated value.

**6.1 Typestate inference rules**

Before introducing the typestate inference rules, we define the typing judgements:

\[
\Delta \vdash e : U \quad \Delta \vdash C[S] \quad \text{class C : S} \quad \{\vec{F}, \vec{M}\} \quad \vec{D}
\]

The first one is the typing judgement for expressions. The judgement is read from right to left. It takes as input the typing context \( \Delta' \) and the expression \( e \), and algorithmically computes the type \( U \). The effects of the expression on \( \Delta' \) are then captured in \( \Delta \). However, it is interesting to notice that the judgement can also be read from left to right in a type system fashion, where the expression “consumes” \( \Delta' \) in order to produce \( \Delta' \). The second judgement infers the typestates of the fields of a class when the class is used according to its declared typestates. The last two typing judgements state the well-formedness of classes and, respectively, programs.

The typestate inference rules for expressions are given in Fig. 6. We illustrate the most important rules using examples. The full typestate derivation of the example code can be found in App. C. The type inference is syntax-driven, meaning that at any point of the derivation there is only one rule that can be applied. Rules Void, Bool, Enum and Null type the constants with their corresponding types.

![Figure 4. Subtyping relation (Symmetric rule S-Rec2 omitted)](image-url)

**Figure 5. Join relation (Symmetric recursion rule omitted)**

![Table 6.1](table-url)

**Table 6.1** (Typestate inference rules).
under any typing context without producing any effect on it, namely the left and right typing contexts are the same. Rules $\text{Strengthen}$ and $\text{Weaken}$ allow arbitrary removal and addition, respectively, of inactive typestate assumptions.

**Typestate Linearity.** In the typestate inference system we adopt linearity in order to forbid aliasing. We use the following example to illustrate the treatment of linearity. Consider the following code that uses the stack-driven approach to enforce a typestate inference based on the type of the returned value:

```
stack pushN(stack) { stack.popAll(stack); continue loop }
```

To conclude, in rules $\text{Asgn}$ and $\text{New}$ the path this is not assignible. In rule $\text{Path}$ the path this is not inferrable.

The other rules for paths and assignments are as follows. Rule $\text{Path}$ infers a constant type $U$ for a path $r$ and has no effect in the input typing context, if $r$ is mapped to $U$ in the input typing context. Rule $\text{Asgn}$ follows the same line as $\text{Asgn}$, the difference being the type of $e$ which is a constant type $U$ that is left unchanged in the input and output typing contexts.

**Recursion and Choice.** We now explain recursion and choice by using an example of a recursive loop. The example is used to explain rules $\text{LE}$, $\text{CONT}$, $\text{Sitch}$, and $\text{In}$. Consider the following class $\text{StackUser}$ that defines methods that use a stack object:

```java
class StackUser {
    {Stack pushN(Stock) { Stack popAll(Stock) ; continue loop })
    {
        Stack pushN(Stock x) { x.push(2) ; x }
        Stack popAll(Stock x)
        (loop : switch(x.isEmpty))
        { case EMPTY : x,
            case NOTEMPTY : x.pop() ; continue loop }
    }
}
```

and $\Delta_0 = x : \text{Stack[end]}, \text{this : StackUser[end], the input typing context. The body of method popAll in line 4 is a labelled expression, and so rule $\text{LE}$ applies. The premise that requires an inference for the switch expression by using in input $\Delta_0$ augmented with the assumption loop : $X$, where $X$ is fresh. Let $\Delta_1 = \Delta_0$, loop : $X$, $\text{LE}$ closes all free occurrences of $X$ in the output typing context. For the switch expression rule $\text{Sitch}$ is used, which requires a typestate inference for all the switch branches. The input typing context for
it is revealed that the body of Stack push(Stack) calls method Stack popAll(Stack) on its receiver object, thus violating the abstraction principle.

**Classes and Programs.** The rules for classes and programs are given in Fig. 7. They make use of inference rules for the fields of a class, which we explain first. The typestates of the fields of a class are inferred when method calls of that class take place. This procedure is described by the inference rules for typestates. Rule **Set-Th** requires the inference and join of the typestates of all branches in an internal choice. Rule **Method-Th** relies on the infer(T) definition that maps a type T to the corresponding inferred type U as: \(U \equiv \text{infer}(T) = T\) \(\vdash\) infer(C) = C[\(\text{end}\)]. Rule **Method-Th** infers a method-prefix typestate, where first it requires an inference of the continuation typestate, and then uses the output typing context to infer the method prefix; it infers a typestate for a method definition by first inferring a typestate for its body. The auxiliary function infer(T) is used to check that the return and parameter types of the method match the types of the inferred ones. As in **Call**, a self-call should preserve the typestate of the receiver up to type equivalence. Rule **Env-Th** is similar to rule **Method-Th**. It requires the inference and join of the typestates of all the external choices and then infers the method prefix. Rule **Env-Th** requires all fields of the class to finish in the inactive typestate. Rules **Rec-Th** and **Var-Th** are similar to rules **Env-Th** and **Continue**, where they bind and use a recursive variable, respectively. Rule **Class-Th** initiates the inference of the typestate of the class. It states that a class declaration is well-typed if every field of the class has an inactive typestate and this is assumed in the typing context in the premise of **Class-Th**. A program is well-typed if all of its classes are well-typed, as stated by rule **Program**. To illustrate the rules, we show a typestate inference for StackUser in App. C.

In Fig. 8 we give the inference rules for runtime expressions. We show only the ones that are different with respect to the rules in Fig. 6. Rule **Switch-Ar** is similar to **Switch**, the difference being the condition of the switch, which is evaluated to an active receiver.

\[
\text{Stack push}(\text{Stack } x) \{ \text{x.push}(2); x \} \in \text{methods(\text{StackUser})} \quad (1) \\
\Delta \vdash c \text{.push}(s)[\text{Stack } s]\vdash \Delta_1 \\
\text{CALL} \quad \Delta \vdash c \text{.push}(s)[\text{Stack } s]\vdash \Delta_1
\]

The premise of **Call** given in (1), performs a lookup in the methods of the class of the receiver, ListCons, to obtain the definition of method **Stack push**. Next, in (2), the premise injects a typestate for the body of the method in which c has been substituted for the keyword this. Both the method call and its body use the same input typing context. The output typing context of the body of the method should contain a typestate assumption for the method parameter and the receiver, as follows: \(\Delta_2 = \Delta_1, x : \text{Stack }\{\text{void push(int )} : S\}\) . Then, in (3) **Call** requires a typestate inference in order to match the typestate of the method parameter with the type of the method call argument. For this rule, **PanR** is used where \(\Delta_1\) also updates the type of the receiver: \(\Delta_1 = s : \text{Stack[end]}, c : \text{StackUser}[\text{Stack push}](\text{Stack }) : \{\text{Stack popAll(\text{Stack }) : end}\}\)
The output typing context and the typestate of the configuration match those of the expression. For a runtime configuration, by first inferring a typestate for the object, we use its output typing context to type the heap.

$$\Delta', C[S] \vdash e : U \vdash \Delta''$$

$$\Delta, \frac{\text{Method-} \text{St}}{T, m(T, x) \{e\} \in \text{methods}(C)} \frac{\forall \ell, S' \xrightarrow{\ell} S \implies S \xrightarrow{\ell} S}{\Delta, C[T, m(T') : S]}$$

$$\Delta, x : C[S'], E \vdash e : \text{infert}(T_1) + \Delta', \text{this: } C[S], x : \text{init}(T')$$

$$\Delta \vdash C[[T, m(T') : S]]$$

$$\Delta, \times : C[S'], E \vdash e : \text{methods}(C)$$

$$\Delta, x : C[S'] \vdash E \vdash m(T, x) \{e\} \vdash e : \Delta''$$

$$\Delta = \text{join}((\Delta)_{r,e} : e)$$

$$\Delta \vdash C[E \vdash m(T) : (S)_{r,e} : e]$$

$$\forall \ell, \Delta, \vdash C[S]$$

$$\Delta = \{r : C[\mu X.S] \mid r : C[S] \in \Delta'\} \cup \{r : U \mid r : U \in \Delta' \text{ and } U \neq C[S] \}$$

$$\Delta \vdash C[\mu X.S]$$

$$\Delta \vdash \text{switch}(e @ r) \{e\}_{r,e} : \text{join}((U)_{r,e} : e) + \Delta'$$

$$\Delta \vdash e : U + \Delta'$$

$$\Delta \vdash e @ r : U + \Delta'$$

$$\Delta \vdash h \vdash e : U + \Delta'$$

$$\Delta \vdash e : U + \Delta'$$

$$\forall r, U \vdash \Delta,$$

$$h(r) = o$$

$$\Delta \vdash o : U + \Delta$$

$$\Delta \vdash h$$

$$\Delta \vdash C[f : o] : C[S'] + \Delta$$

$$\Delta \vdash C[[T, m(T') : S]]$$

$$\Delta, r : C[[T, m(T') : S]] \xrightarrow{\tau m(T')} \Delta, r : C[S]$$

$$\Delta, r, f : C[\{end\}], r' : C[S] \xrightarrow{r \mapsto f} \Delta, r, f : C[S], r' : C[\{end\}]$$

$$(S \xleftarrow{ obst \text{ typestate}(C)} \forall r, f, f' : C[S'] \in \Delta, S' = \text{end})$$

$$\Delta, r, f : C[\{end\}] \xrightarrow{r \mapsto f \text{ new } c} \Delta, r, f : C[S]$$

$$\Delta, r : C[[S]_{r,e} : e] \xrightarrow{r \mapsto f} \Delta', r : C[S']$$

$$\Delta \vdash h, e : U + \Delta'.$$

$$\Delta \vdash h, e \xrightarrow{r \mapsto f \text{ new } c} h', e'$$

$$\Delta \vdash C[[T, m(T') : S]]$$

$$\Delta, r : C[[T, m(T') : S]] \xrightarrow{\tau m(T')} \Delta, r : C[S]$$

$$\Delta, r, f : C[\{end\}], r' : C[S] \xrightarrow{r \mapsto f} \Delta, r, f : C[S]$$

$$\Delta \vdash h, e : U + \Delta'$$. If $h, e \xrightarrow{r \mapsto f \text{ new } c} h', e'$, then $\Delta \vdash C[[T, m(T') : S]]$ with $\Delta = \Delta', r : C[S]$, $S \xleftarrow{ obst \text{ typestate}(C)}$. Subject reduction requires that the trace of the execution of a program is included in the trace of the inferred typestates of the program. Furthermore, we require a progress property on expressions: an expression that is not a value can always reduce. As a corollary of Theorem 6.3, we further observe that the trace of the inferred context of a program is included in the declared typestate of the program. This is stated by the following.

**Theorem 6.3 (Progress and Subject Reduction).** Let a set of declarations $D$ with $\vdash D$. Assuming $D$ is the program context, let $e$ be a run time expression and suppose $\Delta \vdash e : U + \Delta'$. Then, either $e$ is a value, or there exist $f$, $h'$, and $e'$ such that $h, e \xrightarrow{r \mapsto f \text{ new } c} h', e'$, and there exist $\Delta'$ and $U'$ such that $\Delta \xrightarrow{r \mapsto f \text{ new } c} \Delta'$ and $\Delta \vdash h', e' : U' + \Delta''$ and $U' \xleftarrow{ obst } U$.

**Corollary 6.4 (Coherence of Typestate Inference).** Let $D$ be a set of declarations such that $\vdash D$. Assuming $D$ to be the ambient program context, let $e$ be a run time expression and suppose $\Delta \vdash h, e : U + \Delta'$. Then, either $h, e \xrightarrow{r \mapsto f \text{ new } c} h', e'$, for some $\tilde{e}$, then $\Delta \vdash \Delta''$, $r : C[\{end\}]$ with $\Delta = \Delta''$, $r : C[S]$, and $S \xleftarrow{ obst \text{ typestate}(C)}$. We state the progress and subject reduction theorem in the following. The proof is given in App. A.2.

**Theorem 6.3 (Progress and Subject Reduction).** Let a set of declarations $D$ with $\vdash D$. Assuming $D$ is the program context, let $e$ be a run time expression and suppose $\Delta \vdash e : U + \Delta'$. Then, either $e$ is a value, or there exist $f$, $h'$, $e'$ such that $h, e \xrightarrow{r \mapsto f \text{ new } c} h', e'$, and there exist $\Delta'$ and $U'$ such that $\Delta \xrightarrow{r \mapsto f \text{ new } c} \Delta'$ and $\Delta \vdash h', e' : U' + \Delta''$ and $U' \xleftarrow{ obst } U$.

Subject reduction requires that the trace of the execution of a program is included in the trace of the inferred typestates of the program. Furthermore, we require a progress property on expressions: an expression that is not a value can always reduce. As a corollary of Theorem 6.3, we further observe that the trace of the inferred context of a program is included in the declared typestate of the program. This is stated by the following.

**Corollary 6.4 (Coherence of Typestate Inference).** Let $D$ be a set of declarations such that $\vdash D$. Assuming $D$ to be the ambient program context, let $e$ be a run time expression and suppose $\Delta \vdash h, e : U + \Delta'$. Then, either $h, e \xrightarrow{r \mapsto f \text{ new } c} h', e'$, for some $\tilde{e}$, then $\Delta \vdash \Delta''$, $r : C[\{end\}]$ with $\Delta = \Delta''$, $r : C[S]$, and $S \xleftarrow{ obst \text{ typestate}(C)}$. 7. **Related Work**

**Session types and programming languages.** The Session Java (SJ) language [28] builds on earlier work [14, 15, 17] to add binary session type channels to Java. SJ has been applied to a range of
situations including scientific computation [37] and event-driven programming [26]. SJ implements a library for binary sessions that have a pre-defined interface. The Java syntax is extended with communication statements that enable typechecking. The scope of a session is restricted to the body of a single method. Mungo lifts these restrictions by allowing the abstraction of multiparty session types as user-defined objects that can be passed and used throughout different program scopes. Gay et al. [23] outlined an implementation of their type system as a language called Bica, which is not currently maintained and is unusable. Mungo improves on Bica by using type inference to remove the need for typestate declarations on methods.

The work in [26] extends Session Java with runtime type inspection and asynchronous communication semantics to enable an event-driven framework based on binary session types. As a use case they implement a binary session-type SMTP server that uses a reactive structure to handle multiple clients concurrently. In our work we implement an SMTP client by using StMungo, which automatically generates code from a global protocol. Extending Mungo with runtime typestate inspection would enable us to investigate event-driven programming with multiparty session types.

Capecchi et al. [9] proposed that a class defines sessions instead of methods. A session generalises a method to an extended session typed dialogue over a communication channel. As far as we know, this new paradigm has not yet been implemented.

The work in [36] typechecks the operations of a library that implements multiparty session types using a restricted set of MPI [30] primitives. In contrast, our framework typechecks Java statements and expressions, instead of higher-level operations. The work in [35] uses Scribble to automatically generate MPI code based on user-defined kernels that produce and consume data. The generated code does not require typechecking. On the other hand, the StMungo translation can be used together with the Mungo typechecker to develop more flexible multiparty session type implementations.

Monitoring based on Scribble definitions. Neykova et al. [34] have used Scribble protocol definitions to achieve dynamic monitoring in Python, by translating local protocols into finite state machines that intercept communication and check the validity of runtime messages. Subsequently, [33] implements a session-based Actor framework that uses runtime monitoring to integrate multiparty session types. A hybrid approach has been used by Hu [27] to analyse an SMTP client in Java. Hu’s SMTP API implements multiparty session types using a pattern in which each communication method returns the receiver object with a new type that determines which communication methods are available at the next step. If the pattern is used properly then standard Java typechecking can verify correctness of communication, but runtime monitoring is needed to check linearity constraints. In contrast, our analysis of SMTP is able to statically check all aspects of the protocol implementation.

The receiver-returning pattern is at the basis of functional programming with session types [22] and has been used to achieve protocol checking in Idris [29] and as a replacement for explicit typestate in Rust [39].

Typestate. There have been many efforts to add typestate to practical languages, since their introduction in [42]. Vault [12, 19] is an extension of C, and Fugue [13] applies similar ideas to C#. Plural [6] is based on Java and has been used to study access control systems [5] and transactional memory [4], and to evaluate the effectiveness of typestate in Java APIs [6]. In contrast Mungo follows Gay et al. which is inspired by session types; the possible sequences of method calls are explicitly defined, rather than being consequences of pre- and post-conditions. Like Plural, a typestate in Mungo can depend on the return value of a method call.

Sing# [18] is an extension of C# which was used to implement Singularity, an operating system based on message-passing. It incorporates typestate-like contracts, which are a form of session type, to specify protocols. Bono et al. [8] have formalised a core calculus based on Sing# and proved type safety.

Aldrich et al. [2, 43] proposed a new paradigm of typestate-oriented programming, implemented in the Plaid language. Instead of class definitions, a program consists of state definitions containing methods that cause transitions to other states. Transitions are specified in a similar way to Plural’s pre- and post-conditions. Like classes, states are organised into an inheritance hierarchy. The most recent work [20, 44] uses gradual typing to integrate static and dynamic typestate checking. We focus on the object-oriented paradigm in order to be able to apply our results to Java.

Bodden and Hendren [7] developed the Clara framework, which combines static typestate analysis with runtime monitoring. The monitoring is based on the tracematches approach [3], using regular expressions to define allowed sequences of method calls. The static analysis attempts to remove the need for runtime monitoring, but if this is not possible, the runtime monitor is optimised. Mungo uses a purely static analysis, and can allow the state after a method call to depend on the method’s (enumerated type) result.

Typestate systems must control aliasing; otherwise method calls via aliases can cause inconsistent state changes. Literature includes the “adoption and focus” approach of Vault and Fugue, the permission-based approaches of Plural and Plaid, and an expressive fine-grained system by Militão et al. [31]. Also relevant is recent work by Crafa and Padovani [11] which applies the chemical approach to concurrent typestate oriented programming, allowing objects to be accessed and modified concurrently by several processes, each potentially changing only part of their state. We expect that many of these systems can be applied to Mungo. However, linear typing has not been a limiting factor for the applications described in the present paper.

8. Concluding Remarks and Future Work

Concluding Remarks. We have presented two tools, Mungo and StMungo, which extend the Java development process with support for static typechecking of communication protocols. Mungo extends Java with typestate definitions, which associate classes with state machines that implement permitted sequences of method calls. StMungo uses the typestate feature to connect Java to Scribble, the latter being a language used to specify communication protocols. In order to illustrate the practicality and robustness of Mungo and StMungo, we have implemented a substantial use case, an SMTP server, which we were able to statically typecheck. We use this client to communicate with the @gmail server. Finally, we have formalised the essential features of Mungo by defining a typestate inference system for a core object-oriented language. We proved safety and progress properties (Theorem 6.3). Theorem 5.2 These properties guarantee the coherence of the typestate inference system with respect to the declared typestate in a program (Corollary 6.4).

Future Work. The combination of Mungo and StMungo is effective for statically checking the correct implementation of communication protocols. We intend to extend Mungo to increase its power for general-purpose programming with typestate. Our first aim is to generalise the use of linear typing as a mechanism for the alias control required by typestate systems. Candidates include the “adoption and focus” technique of Vault and Fugue, the permission-based approaches of Plural and Plaid, and the system by Militão et al. [31]. Another aim is to support generics and inheritance. Inheritance between typestate classes requires a subtyping relation between their typestate specifications, based on standard definitions of subtyping for session types [21]. Method calls on an object whose type is a generic parameter must be typechecked against the typestate specification of the parameter’s upper bound. To extend typechecking to exception handlers, we need to allow typestate specifications to define the state transitions corresponding
to exceptions, and check that these transitions are consistent with the states of fields at the point where an exception is thrown. Existing work on exceptions in session types [10] provides inspiration, but doesn’t address the complexities of Java’s exception mechanism. Using these Mungo extensions with SMungo for more sophisticated protocol verification will also require extensions to Scribble to support generic protocols, inheritance between protocols, and more general handling of exceptions.

Acknowledgements This research was supported by UK EPSRC grant EP/K034413/1 From Data Types to Session Types: A Basis for Concurrency and Distribution. We thank Laura Voinea for her contribution to Mungo and SMungo. We thank Garrett Morris, Raymond Hu and Nobuko Yoshida for useful comments and discussion.

References

A. Progress and Subject Reduction

A.1 Auxiliary Results

In the following we use $\Delta(v : U)$ to denote $\Delta$ where the value $v$ is updated to the type $U$.

Lemma A.1 (Typability of Heap Update). Let $h$ be a heap and $r$ a runtime path such that $\Delta \vdash h$ and $r : U \in \Delta$.

1. If $U \equiv C[S]$ and $\Delta \vdash o : U \oplus \Delta$, then $\Delta \vdash h[r \mapsto o]$.
2. If $U = C[S]$ and $\Delta \vdash o : C[S'] \rightarrow \Delta'$, then $\Delta \vdash h[r \mapsto o]$, where $\Delta' = \Delta [r : C[S']]$.

Proof. Both cases follow by using rule $\text{Heap}$ and for 1. typing rules for constants are used, and for 2. rule $\text{Object}$ is used.

Lemma A.2 (Replacement). If

- $d$ is a derivation for $\Delta \vdash E[e] : U \oplus \Delta'$,
- $d'$ is a subderivation of $d$ concluding $\Delta \vdash e : U \oplus \Delta_e$,
- the position of $d'$ in $d$ corresponds to the position of the hole in $E$,
- $\Delta' \vdash e' : U \oplus \Delta_e$, such that $U \vdash_{\text{set}} e'$,

then $\Delta \vdash E[e'] : U \oplus \Delta'$ such that $U \vdash_{\text{set}} U'$.

Proof. Follows [23], by replacing the derivation $d'$ in $d$ with the derivation for $\Delta' \vdash e' : U \oplus \Delta_e$.

Lemma A.3 (Substitution). 1. If $\Delta, x : U \vdash e : U \oplus \Delta$ and $\Delta[v : U'] \vdash v : U' \oplus \Delta'$, then $\Delta[v : U'] \vdash e[v/x] : U \oplus \Delta'$.

2. Assume $\Delta_1 \vdash e : U \oplus \Delta$, $\lambda x. \Delta_2 \vdash e' : U \oplus \Delta'$.

Then, $\Delta \vdash e[e'/\text{continue }\lambda] : U \oplus \Delta'$ with

$$
\Delta = \begin{cases}
[r : C[S'/X]] & | r : C[S] \in \Delta_1 \text{ and } r : C[S'] \in \Delta_2 \\
[r : U'] & | r : U' \in (\Delta_1 \cup \Delta_2)U' \neq C[S'] \\
\Delta_1 \setminus \Delta_2 \cup \Delta_2 \setminus \Delta_1
\end{cases}
$$

Proof. The proof proceeds by induction on the last typing rule used for the assumed judgement. The second case uses Lemma A.2.

Lemma A.4 (Subtyping and join). The following relate subtyping and join on inferred types $U$ and typing contexts $\Delta$.

- Let $U, U'$ be inferred types such that $\text{join}(U, U')$ is defined. Then, $U \vdash_{\text{set}} \text{join}(U, U')$ and $U' \vdash_{\text{set}} \text{join}(U, U')$.

- Let $\Delta, \Delta'$ such that $\text{join}(\Delta, \Delta')$ is defined. Then, $\Delta \vdash_{\text{set}} \text{join}(\Delta, \Delta')$ and $\Delta \vdash_{\text{set}} \text{join}(\Delta, \Delta')$.

Proof. The proof follows immediately by combining the definition of subtyping in Fig. 4 and the definition of join Fig. 5.

Lemma A.5 (Typability of Subterms). If $d$ is a derivation for $\Delta \vdash E[e] : U \oplus \Delta'$ then there exist $\Delta'$ and $U'$ such that $d$ has a subderivation $d'$ concluding $\Delta \vdash e : U' \oplus \Delta'$ and the position of $d'$ in $d$ corresponds to the position of the hole in $E$.

Proof. The proof proceeds by induction on the structure of context $E$.

- $E = [\vdash]$; follows trivially by assumption.

- $E = r.m(E')$: by assumption $\Delta \vdash r.m(E'[e]) : U \oplus \Delta''$. By inversion on rule $\text{Call} \Delta \vdash E[e] : U \oplus \Delta''$, $r : C[[T m(T') : S]]$, where the typing context $\Delta''$ and the type of $r$ are inferred by the premise of $\text{Call}$. We conclude by induction hypothesis on $E'$.

- $E = r.f = E'$: by assumption $\Delta \vdash r.f = E'[e] : U \oplus \Delta'$. There are two rule that can be applied for assignment, rule $\text{AssignC}$ and rule $\text{AssignR}$. By inversion on the former we obtain $\Delta \vdash E'[e] : U \oplus \Delta''$, $r : U$; by inversion on the latter we obtain $\Delta \vdash E'[e] : C[S] \oplus \Delta''$, $r : C[end]$, where the typing context $\Delta''$ and the type for $r$ are inferred by the premise of the rule. We conclude by induction hypothesis on $E'$.

- $E = E'; e'$: by assumption $\Delta \vdash E'[e] ; e' : U \oplus \Delta''$. By inversion on rule $\text{Seq} \Delta \vdash E'[e] ; e' : U'' \oplus \Delta'''$, where the typing context $\Delta'''$ and the type $U''$ are inferred by the premise of the rule. We conclude by induction hypothesis on $E'$.

The rest of the cases follow the same idea as the above.

A.2 Progress and Subject Reduction

Proof of Theorem 6.3: Let $\widetilde{D}$ be a set of declarations such that $\vdash \widetilde{D}$. In a context parametrized by $\widetilde{D}$, let $e$ be a run time expression and suppose $\Delta \vdash h, e : U \oplus \Delta'$.

Then, either $e$ is a value, or there exist $\ell, h'$ and $e'$ such that $h, e \xrightarrow{\ell} h', e'$, and there exist $\Delta'$ and $U'$ such that $\Delta \xrightarrow{\ell} \Delta'$ and $\Delta' \vdash h' \oplus e' : U' \oplus \Delta''$ and $\Delta' \vdash h \oplus e' : U' \oplus \Delta''$ and $\Delta' \vdash_{\text{set}} U$. Proof. The proof proceeds by induction on the structure of the expression $e$ with respect to contexts. We present first the inductive case. Let $e = E[e_1]$ where $e_1$ is not a value and $E \neq [\vdash]$. By assumption and inversion on rule $\text{Config}$ we have $\Delta \vdash E[e_1] : U \oplus \Delta'$. By Lemma A.5 there exist $\Delta_1$ and $U_1$ such that $\Delta \xrightarrow{\ell} \Delta'$ and $\Delta' \vdash e_1 : U_1 \oplus \Delta_1$. By induction hypothesis there exist $h', \ell$ such that $h, e_1 \xrightarrow{\ell} h', e_2$. By induction hypothesis we also have $\Delta \xrightarrow{\ell} \Delta'$ and $\Delta' \vdash h, e_2 : U_2 \oplus \Delta_1$, which by inversion on $\text{Config}$ means that $\Delta' \vdash h$ and $\Delta' \vdash e_2 : U_2 \oplus \Delta_1$, where $U_2 \vdash_{\text{set}} U_1$. By rule $\text{R-Ctx}$ we have $h, E[e_1] \xrightarrow{\ell} h', E[e_2]$. By Lemma A.2 we obtain $\Delta' \vdash E[e_2] : U' \oplus \Delta''$ with $U' \vdash_{\text{set}} U$. We conclude by rule $\text{Config}$.

The base cases when $e$ is of the form $E[v]$ with $E$ elementary, not being of the form $E[E']$ with $E' \neq [\vdash]$, and not of the form $E[e_1]$ are in the following. If $e$ is a value, then there is nothing to prove. If $e$ is not a value, by the operational semantics rules, we have the following cases for $e$ with respect to contexts.
We conclude by Lemma A.1.

We have to prove that

where

such that

By reduction rule $\TvIo \Delta \xrightarrow{\sigma} \Delta$. Since $U' \neq C[S]$ and value $v$ is of type $U'$ it means $v$ is some constant $c$. Hence, the judgement $\Delta \vdash v : U' \vdash \Delta$ is obtained by applying one of the following typing rules: $\Void$, $\Enum$, or $\Bool$. By inversion this implies $\Delta = \Delta'$. Then, by rewriting the premise of the typing rule for $e'$ we have $\Delta \vdash e' : U \vdash \Delta''$. We conclude by rule $\Config$.

$e = (r.f = c)$. By hypothesis and by rule $\RAsgnC$

By hypothesis and by rule $\Config \Delta \vdash h$ and $\Delta \vdash r.f = c : U \vdash \Delta'$. By inversion and typing rule $\AsgnC$ we have

where $U = \Void$ and $\Delta' = \Delta'$, $r.f : U'$. Since the value assigned to $r.f$ is a constant $c$ the judgement of the premise $\Delta \vdash c : U' \vdash \Delta'$, $r.f : U'$ must have been obtained by one of the following typing rules: $\Void$, $\Enum$, or $\Bool$. This implies that $\Delta = \Delta'$, $r.f : U'$. By $\TvIo$, $\Delta \xrightarrow{\sigma} \Delta$. We have to prove that $\Delta \vdash h(r.f \mapsto c), * : \Void \vdash \Delta', r.f : U'$. By rule $\Void$, $\Delta \vdash * : \Void \vdash \Delta'$, $r.f : U'$. Recall that, by hypothesis and rule $\Heap$ and inversion we have

By updating the heap to $h[r.f \mapsto c]$, using the typing judgement for $c$ in the premise of $\AsgnC$ and Lemma A.1 we derive $\Delta', r.f : U' \vdash h[r.f \mapsto c]$. We conclude by rule $\Config$.

$e = (r.f = r')$. By hypothesis and by rule $\RAsgnR$

where $h' = h[r' \mapsto \nul1]$. By hypothesis and by rule $\Config \Delta \vdash h$ and $\Delta \vdash r.f = r' : U \vdash \Delta''$. By inversion and typing rule $\AsgnR$

where $U = \Void$ and $\Delta' = \Delta$, $r.f : C[S]$ and for readability let $\Delta = \Delta$, $r.f : C[S]$. Let $r' \neq r.f$. Since $r'$ is a path typed by $C[S]$, the premise of the above derivation is obtained by applying $\PathR$. This implies that contexts $\Delta$ and $\Delta_2$ differ only in the typing of $r'$. By
inversion, $\Delta(r,f) = \Delta_2(r,f) = \{c\text{end}\}$ and $\Delta(r') = \{\text{S}\}$ and $\Delta_3(r') = \{\text{end}\}$. By rule TV-ASGNR

$$\frac{\Delta_3, r' : \{\text{S}\}, r.f : \{c\text{end}\} \vdash \{f\}}{\Delta_3, r.f : \{\text{S}\}, r' : \{\text{end}\}}$$

where $\Delta = \Delta_1, r' : \{\text{S}\}, r.f : \{\text{end}\}$ and $\Delta' = \Delta_2, r' : \{\text{S}\}, r' : \{\text{end}\}$. Since $\Delta'' = \Delta'$, by applying rule Vow we conclude $\Delta' : \top : \text{void} + \Delta''$. It remains to prove that

$$\frac{\Delta_3, r.f : \{\text{S}\} , r' : \{\text{end}\} \vdash h'[r.f \mapsto h(\text{r})]}{\Delta_3, r.f : \{\text{S}\} , r' : \{\text{end}\} \vdash h}$$

where $h' = h[\text{r} \mapsto \text{null}]$. Recall that

$$\Delta_3, r' : \{\text{S}\}, r.f : \{\text{end}\} \vdash h$$

The result follows immediately by applying twice Lemma A.1 for $r.f$ and $r'$. We conclude by ConsO. Let $r' = r.f$. By rewriting AsgnR with $r.f$ instead of $r'$ we notice that the derivation holds if $S = \text{end}$. Then the proof proceeds trivially.

- $e = r.m(v)$. By hypothesis and by rule R-Call

$$h, r, m(v) \xrightarrow{e.T} h, r, e[v/x][r/this]\{\text{f} - \rightarrow \text{a}\}$$

such that $h(r) = C[f \mapsto \text{a}]$ and $T (m(T' x) \{e\}) \in \text{methods}(C)$. By hypothesis and by rule $\text{Config} : \Delta \vdash h$ and $\Delta \vdash r.m(v) : U + \Delta''$. By inversion and typing rule Call

$$\frac{T \vdash m(T' x) \{e\} \in \text{methods}(C)}{\Delta, r : \{\text{S}\}\vdash h}$$

where $\Delta'' = \Delta_1, r : \{\text{S}\}$ and for readability let $\Delta'' = \Delta_2, r : \{\text{S}\} = \{\text{I} m(T') : \{\text{S}\}\}$. Notice that $v \neq r$, otherwise the method call $r.m(v)$ would not be well-typed. Then, $\Delta(r) = \Delta'''(r) = C[(m(T') : \{\text{S}\})]$. Let $\Delta = \Delta_3, r : \{\text{S}\} = \{\text{I} m(T') : \{\text{S}\}\} \vdash \text{By TV-Call}$

$$\Delta_3, r : \{\text{S}\} = \{\text{I} m(T') : \{\text{S}\}\} \vdash r.m(v) : U + \Delta''$$

We need to prove that $\Delta_3, r : \{\text{S}\} \vdash h$ and also $\Delta_3, r : \{\text{S}\} \vdash e[v/x][r/this]\{\text{f} - \rightarrow \text{a}\} \vdash r : U + \Delta''$. By ArR it suffices to show $\Delta_3, r : \{\text{S}\} \vdash e[v/x][r/this] : U + \Delta''$. By the premise of Call,

$$\Delta, r : \{\text{S}\}, x : U' \vdash e[r/this] : U + \Delta_1, r : \{\text{S}\}\vdash h$$

we can notice that $\Delta_2$ and $\Delta_3$ are such that either $\Delta_2 = \Delta_3$ with $\Delta_2(v) = \Delta_3(v) = U'$ or $\Delta_2(v) = U''$ and $\Delta_3(v) = U'/v : U''$. By Lemma A.3 we have

$$\Delta_3, r : \{\text{S}\} \vdash e[v/x][r/this] : U + \Delta_1, r : \{\text{S}\}\vdash h$$

Since $S = \Delta_2 S'$, we conclude by rule Equiv. Recall that $\Delta_3, r : \{\text{S}\} = \{\text{I} m(T') : \{\text{S}\}\} \vdash h$. By Hap we have

$$h(r) = C[f \mapsto \text{a}] \vdash C[f \mapsto \text{a}] : C[(m(T') : \{\text{S}\})] \vdash \Delta$$

which by Object it means that

$$\frac{\text{typestate}(C) = S\{C\} \overset{\tau}{\rightarrow} (m(T') : \{\text{S}\})}{\Delta \vdash C[f \mapsto \text{a}] : C[(m(T') : \{\text{S}\})] \vdash \Delta}$$

We perform another reduction with label $T m(T)$ and we have

$$\frac{\text{typestate}(C) = S\{C\} \overset{\tau}{\rightarrow} (m(T') : \{\text{S}\}) \overset{T(m(T))}{\rightarrow} S}{\Delta, r : \{\text{S}\} \vdash C[f \mapsto \text{a}] : C[S] \vdash \Delta_3, r : \{\text{S}\}\vdash h}$$

We now can type $\Delta_3, r : \{\text{S}\} + h$ by rule Hap. We conclude by rule Config.

- $e = v \top r$. By hypothesis and by rule R-Value

$$h, v \top r \xrightarrow{r} h, v$$

for $v \neq l$. By hypothesis and by rule Config $\Delta \vdash h$ and $\Delta \vdash v \top r : U + \Delta''$. By inversion and typing rule ArR

$$\frac{\Delta \vdash v : U + \Delta''}{\Delta \vdash v \top r : U + \Delta''}$$

By reduction rule TV-In $\Delta \overset{r}{\rightarrow} \Delta$. The thesis follows trivially.

- $e = \text{switch}(l' \top r) \{e_l\}_{l \in E}$. By hypothesis and by rule R-Switch

$$h, \text{switch}(l' \top r) \{e_l\}_{l \in E} \xrightarrow{c(f)} h, e_f$$

for some $l' \in E$. By hypothesis and by rule Config $\Delta \vdash h$ and $\Delta \vdash \text{switch}(l' \top r) \{e_l\}_{l \in E} : U + \Delta''$. By inversion and typing rule Switch-ArR

$$\frac{\forall l \in E \quad \Delta_1, r : \{\text{S}\} + e_l : U + \Delta'' \quad \Delta \vdash l' : E + \Delta_1, r : \{l : \{\text{S}\}\}_{l \in E}}{\Delta \vdash \text{switch}(l' \top r) \{e_l\}_{l \in E} : \{\text{join}(U)\}_{l \in E} \vdash \Delta''}$$

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where \( U = \text{join}((U_1 \downharpoonright S)_{i \in E}) \). By inversion and typing rule Enum we have that \( \Delta = \Delta_1 ; r : C((l : S)_{i \in E}) \). By Tv-Label
\[
\Delta_1 ; r : C((S)_{i \in E}) \xrightarrow{t(v)} \Delta_2 ; r : C(S) \]
where \( l' \in E \) and \( \Delta' \triangleleft_{\text{set}} \Delta \). By Lemma A.4 we have that \( \Delta_2 \triangleleft_{\text{set}} \text{join}((U)_{l \in E}) \). The judgement \( \Delta_2 ; r : C(S) \vdash e_r : U \triangleq \Delta'' \) holds by the premise of Switch for \( l' \in E \). We need to prove that \( \Delta_2 ; r : C(S) \vdash h \). Recall that, by hypothesis \( \Delta \vdash h \). By Heap and Object it means that there exist \( \exists \), such that typestate \( C = S \) and \( S \xrightarrow{t(v)} (l : (S)_{i \in E}) \) and
\[
\Delta \vdash C[f/o] : C((l : S)_{i \in E}) \vdash \Delta
\]
By Definition 6.2, we have \( (l : S)_{i \in E} \xrightarrow{t(v)} S \) \( F \). By applying rule Object on this reduction, we have
\[
\Delta_2 ; r : C(S) \vdash C[f/o] : C(S) \triangleq \Delta_2 ; r : C(S)
\]
We conclude by rules Heap and Config.

- \( e = \text{if (tt) } e_1 \text{ else } e_2 \). The case for \( \text{if (ff) } e_1 \text{ else } e_2 \) is completely analogous. By hypothesis and by rule R-True
\[
\text{if (tt) } e_1 \text{ else } e_2 \xrightarrow{t(v)} h, e_1
\]
By hypothesis and by rule Config \( \Delta \vdash h \) and \( \Delta \vdash \text{if (tt) } e_1 \text{ else } e_2 : U \triangleq \Delta'' \). By inversion and typing rule If
\[
\Delta_1 \vdash e_1 : U_1 \triangleq \Delta'' \quad \Delta_2 \vdash e_2 : U_2 \triangleq \Delta''
\]
\[
\Delta_3 = \text{join}(\Delta_1, \Delta_2) \quad \Delta \vdash \text{tt : } \text{bool} \triangleq \Delta_3
\]
\[
\Delta = \text{if (tt) } e_1 \text{ else } e_2 : \text{join}(U_1, U_2) \triangleq \Delta''
\]
Where \( U = \text{join}(U_1, U_2) \). Rule Boos implies that \( \Delta = \Delta_1 \). By typing rule \( \text{if (tt) } e_1 \text{ else } e_2 : U \triangleq \Delta'' \). By Lemma A.4 we have that \( U_1 \triangleleft_{\text{set}} \text{join}(U_1, U_2) \). Then, \( \Delta_1 \vdash e_1 : U_1 \triangleq \Delta'' \) follows directly by the premise of \( \text{if (tt) } e_1 \text{ else } e_2 \) and by letting \( \Delta = \Delta_1 \), since \( \Delta_1 \triangleleft_{\text{set}} \text{join}(\Delta_1, \Delta_2) = \Delta \). It remains to prove that \( \Delta_2 \vdash h \). Since \( \Delta_2 \triangleleft_{\text{set}} \Delta \), the thesis follows trivially by applying Heap.

- \( e = (l : e') \). By hypothesis and by rule R-Label
\[
h, \lambda : e' \xrightarrow{t(v)} h, \lambda[e'/\text{continue } \lambda]
\]
By hypothesis and by rule Config \( \Delta \vdash h \) and \( \Delta \vdash \lambda : e' : U \triangleq \Delta' \). By inversion and typing rule LExpr we get
\[
\Delta' \vdash e' : U \triangleq \Delta', \lambda : X
\]
\[
\Delta = \{ r : C[S[X]] | r : C[S] \in \Delta' \} \cup \{ r : U' | r : U' \in \Delta'' \text{ and } U' \neq C[S'] \}
\]
By rule Tv-Label \( \Delta \xrightarrow{t(v)} \Delta \). Since \( \Delta \vdash h \), it remains to prove that \( \Delta \vdash e'[\lambda : e'/\text{continue } \lambda] : U \triangleq \Delta' \). From the second case of the Substitution Lemma A.3 we get:
\[
\Delta'' \vdash e'[\lambda : e'/\text{continue } \lambda] : U \triangleq \Delta'
\]
with
\[
\Delta'' = \{ r : C[S[X]] | r : C[S] \in \Delta' \text{ and } r : C[S[X]] \in \Delta \}
\]
\[
\cup \{ r : U' | r : U' \in \Delta'' \text{ and } U' \neq C[S'] \}
\]
From the definition of \( \Delta'' \) we can obtain that \( \Delta'' = \Delta \) as required. We conclude by rule Config.

## B. StMungo for Multiparty Session Types

In this section we illustrate StMungo on a multiparty protocol that models the process of booking flights through a university travel agent.

There are three participants involved: Researcher (abbreviated R), who intends to travel; Agent (A), who is able to make travel reservations; and Finance (F), who approves expenditure from the budget. In the Scribble language, we first define the global protocol among three roles, which are abstract representations of the participants. The protocol consists of sequences of interactions. Every message (e.g. request) can be associated with a payload type (e.g. Travel1), a sender, and one or more receivers. Typically payload types are structured data types defined separately from the protocol specification.

In the following global protocol, after the quote and the check message requesting authorisation for a trip, Finance can choose to approve or refuse the request:

```plaintext
1 global protocol BuyTicket(role R, role A, role F){
2 request(Travel) from R to A;
3 quote(Price) from A to R;
4 check(Price) from R to F;
5 choice at F {
6 approve(Code) from F to R,A;
7 ticket(String) from A to R;
8 invoice(Code) from A to F;
9 payment(Price) from F to A;
10 } or {
11 refuse(String) from F to R,A; }
```
The Scribble toolchain can be used to check the protocol definition for well-formedness and to derive a local version of the protocol for each role, according to the theory of multiparty session types [25]. This is known as endpoint projection. Here we show the projection for Researcher, which describes only the messages involving that role. The self keyword indicates that R is the local endpoint.

```markdown
local protocol BuyTicket_R(self R, role A, role F) {
  request(Travel) to A;
  quote(Price) from A;
  check(Price) to F;
  choice at F {
  approve(Code) from F;
  ticket(String) from R;
} or {
  refuse(String) from F; }
}
```

Notice that the exchange of invoice and payment between Agent and Finance is not included. Similarly, the local projection for Agent omits the check message and the local projection for Finance omits the request, quote and ticket messages.

For the R role, StMungo converts the `BuyTicket_R` local projection into the following .mungo files:

1. `RProtocol`, capturing the interactions local to the R role as a typestate specification.
2. `RRole`, a class that implements `RProtocol` by communication over Java sockets. This is an API that can be used to implement the Researcher endpoint.
3. `RMain`, a skeletal implementation of the Researcher endpoint. This runs as a Java process, and provides a `main()` method which uses `RRole` to communicate with the other parties in the session.

The `RProtocol` definition generated by StMungo is as follows:

```markdown
typestate RProtocol {
  State0 = {
    void send_requestTravelToA(Travel): State1 }
  State1 = {
    Price receive_quotePriceFromA (): State2 }
  State2 = {
    void send_checkPriceToF(Price): State3 }
  State3 = {
  Choice1 receive_Choice1LabelFromF ():  
    <APPROVE: State4, REFUSE: State6> }
  State4 = {
    Code receive_approveCodeFromF (): State5 }
  State5 = {
    String receive_ticketStringFromA(): end }
  State6 = {
    String receive_refuseTravelFromF(): end }
}
```

```java
class RRole typestate RProtocol {
   /* Constructor and method definitions. */
}
```

Finally, `RMain` provides skeletal implementation of the Researcher endpoint, using the `RRole` class to communicate with the other roles in the system:

```java
public static void main(String[] args) {
  RRole r = new RRole();
  Travel t = // input travel;
  r.send_requestTravelToA(t);
  Price p = r.receive_quotePriceFromA();
  r.send_checkPriceToF(p);
  switch(r.receive_Choice1LabelFromF())
  .getEnum()) {
    case APPROVE:
      Code c = r.receive_approveCodeFromF();
      println(r.receive_ticketStringFromA());
      break;
    case REFUSE:
      println(r.receive_refuseStringFromF());
      break; }
}
```

As we already stated for SMTP, typically the programmer would flesh out the skeletal implementation with extra business logic. Mungo is able to statically check `RMain`, or any client of the `RRole` class, to ensure that methods of the protocol are called in a valid sequence and that all possible responses are handled.
C. Type Inference Examples

C.1 Typestate Linearity
Consider the following code that uses the implementation of class Stack in section § 1:

```java
s = new Stack; k = s
```

Also assume input typing context $\Delta_0 = [s: Stack[end], k: Stack[S]]$. The inference tree for the above code is:

```
PvM
$\Delta_2 = s: Stack[S], k: Stack[end]$ New $\Delta_3 = s: Stack[end], k: Stack[end]$ $s = new Stack; k = s: void + \Delta_0$
\qquad $\Delta_2 + s: Stack[S] + \Delta_1$ 
\qquad $\Delta_1 = s: Stack[end], k: Stack[end]$ 
\qquad $\Delta_2 + k = s: void + \Delta_0$ 
ASGN 
\qquad $\Delta_2 + x: Stack[S] + \Delta_0$ $\Delta_1 + s: Stack[end], k: Stack[end]$ $\Delta_3 + s = new Stack: void + \Delta_2$ 
SEQ
```

C.2 Recursion and Choice
Consider a class StackUser that defines methods that use a Stack object:

```java
class StackUser { {Stack pushN(Stack) : {Stack popAll(Stack):end}} }
Stack pushN(Stack x) {
    x.push(2); x
}
Stack popAll(Stack x) {
    loop :
    switch(x.isEmpty()) {
        case TRUE: x
        case FALSE: x.pop(); continue loop
    }
}
```

Method Stack popAll(Stack): Consider the input typing context $\Delta_0 = x: Stack[end], this: StackUser[end] and e is the switch expression in the body of method Stack popAll(Stack). The inference tree for the body of method Stack popAll(Stack) is:

```
CALL ...
$\Delta_1 = x: Stack[[int pop(): X]], this: StackUser[X]$ 
\quad $\Delta_1 + x.pop(): int + \Delta_1'$ 
\quad $\Delta_1' = x: Stack[X], this: StackUser[X]$ 
\quad $\Delta_1' + continue loop: bot + \Delta_0, loop: X$ 
CONTINUE 
\quad $\Delta_1 + x.pop(); continue loop: bot + \Delta_0, loop: X$ 
PvM
\qquad $\Delta_2 = x: Stack[S], this: StackUser[end], loop: X$ 
\quad $\Delta_2 + x: Stack[S] + \Delta_0, loop: X$ 
SEQ
\qquad $\Delta_3 = x: Stack[Choice isNotEmpty(): join(S, int pop(): X)], this: StackUser[join(end, X)]$ 
\quad $\Delta_3 + x.isEmpty(): Choice + join(\Delta_1, \Delta_2)$ 
\quad $\Delta_3 + e: Stack[S] + \Delta_0, loop: X$ 
\quad $\Delta_4 = x: Stack[\mu X. Choice isNotEmpty(): join(S, int pop(): X)], this: StackUser[\mu X.join(end, X)]$ 
\quad $\Delta_4 + loop: e: Stack[S] + \Delta_0$ 
\quad $end = \mu X. join(end, X)$ 
LEXP 
\quad $\Delta = x: Stack[\mu X. Choice isNotEmpty(): join(S, int pop(): X)], this: StackUser[end]$ 
\quad $\Delta + loop: e: Stack[S] + \Delta_0$ 
EQUIV
```
Method **Stack pushN(Stack)**: Assume a typing context \( \Delta_0 = x : \text{Stack}[\text{end}], \text{this} : \text{StackUser}[[\text{Stack popAll}(\text{Stack}) : \text{end}]]. \) The inference tree for method \( \text{Stack pushN}(\text{Stack}) \) is:

\[
\begin{align*}
\text{PathR} \\
\Delta_1 = x : \text{Stack}[\text{S}], \text{this} : \text{StackUser}[[\text{Stack popAll}(\text{Stack}) : \text{end}]] \\
\Delta_1 \vdash x : \text{Stack}[\text{S}] \vdash \Delta_0 \\
\text{Call} \\
\ldots \\
\Delta = x : \text{Stack}[[\text{void push(int)} : \text{S}]], \text{this} : \text{StackUser}[[\text{Stack popAll}(\text{Stack}) : \text{end}]] \\
\Delta \vdash x.\text{push}(2) : \text{void} \vdash \Delta_1 \\
\Delta \vdash x.\text{push}(2) : x : \text{Stack}[\text{S}] \vdash \Delta_0
\end{align*}
\]

### C.3 Method Call

Consider the code

\[
s = c.\text{pushN}(s)
\]

with input context \( \Delta_0 = s : \text{Stack}[\text{S}], c : \text{StackUser}[[\text{Stack popAll}(\text{Stack}) : \text{end}]]. \) The derivation tree for the above code is:

\[
\begin{align*}
&c.\text{pushN}(\text{Stack} \ x) \ x.\text{push}(2) : x \in \text{methods}(\text{StackUser}) \\
&\text{Seq} \\
&\text{Stack pushN(Stack) method body inference} \\
&\Delta_2 = \Delta_1, x : \text{Stack}[[\text{void push(int)} : \text{S}]] \\
&\Delta_2 \vdash x.\text{push}(2) : x/c/\text{this} : \text{Stack}[\text{S}] \vdash \Delta_1 \\
&\text{PathR} \\
&\Delta_3 = s : \text{Stack}[[\text{void push(int)} : \text{S}]], \\
&\text{}c : \text{StackUser}[[\text{Stack popAll}(\text{Stack}) : \text{end}]] \\
&\Delta_3 \vdash s : \text{Stack}[[\text{void push(int)} : \text{S}]] \vdash \Delta_2 \\
&\Delta = s : \text{Stack}[[\text{void push(int)} : \text{S}]], \\
&c : \text{StackUser}[[\text{Stack pushN(Stack)} : \text{Stack popAll}(\text{Stack}) : \text{end}]] \\
&\text{Call} \\
&\Delta \vdash c.\text{pushN}(s) : \text{Stack}[\text{S}] \vdash \Delta_1 \\
&\Delta_1 = s : \text{Stack}[\text{end}], c : \text{StackUser}[[\text{Stack popAll}(\text{Stack}) : \text{end}]], x : \text{Stack}[\text{end}] \\
&\Delta \vdash s = c.\text{pushN}(s) : \text{void} \vdash \Delta_0
\end{align*}
\]

### C.4 Class inference

The inference tree for class **StackUser** is:

\[
\begin{align*}
\text{Class} \\
\text{Set-ST} \\
\text{Method-ST} \\
\text{LEXP} \\
\text{}x : \text{Stack}[[\text{S}, \text{int pop()} : \text{X}]], \text{this} : \text{StackUser}[\text{end}] \\
\text{End-ST} \\
\vdash \text{StackUser}[\text{end}] \\
\text{Method-ST} \\
\vdash \text{StackUser}[[\text{Stack popAll}(\text{Stack}) : \text{end}]] \\
\text{Set-ST} \\
\vdash \text{StackUser}[[\text{Stack popAll}(\text{Stack}) : \text{end}]] \\
\text{Seq} \\
\text{Stack pushN(Stack) method body inference} \\
\Delta_1 = x : \text{Stack}[[\text{void push(int)} : \text{S}]], \text{this} : \text{StackUser}[[\text{Stack popAll}(\text{Stack}) : \text{end}]] \\
\Delta_1 \vdash x.\text{pushN}(\text{Stack} \ x) \ x.\text{push}(2) : x \in \text{methods}(\text{StackUser}) \\
\vdash \text{StackUser}[[\text{Stack pushN(Stack)} : \text{Stack popAll}(\text{Stack}) : \text{end}]] \\
\vdash \text{StackUser}[[\text{Stack pushN(Stack)} : \text{Stack popAll}(\text{Stack}) : \text{end}]] \\
\vdash \text{StackUser}[[\text{Stack pushN(Stack)} : \text{Stack popAll}(\text{Stack}) : \text{end}]] \\
\vdash \text{StackUser}
\end{align*}
\]