

Communication-Safe Web Programming in TypeScript with Routed Multiparty Session Types

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Abstract

Modern web programming involves coordinating interactions between browser clients and a server. Typically, the interactions in web-based distributed systems are informally described, making it hard to ensure correctness, especially *communication safety*, i.e. all endpoints progress without type errors or deadlocks, conforming to a specified protocol.

We present STScript, a toolchain that generates TypeScript APIs for communication-safe web development over WebSockets, and RouST, a new session type theory that supports multiparty communications with routing mechanisms.

STScript provides developers with TypeScript APIs generated from a communication protocol specification based on RouST. The generated APIs build upon TypeScript concurrency practices, complement the event-driven style of programming in full-stack web development, and are compatible with the Node.js runtime for server-side endpoints and the React.js framework for browser-side endpoints.

RouST can express multiparty interactions routed via an intermediate participant. It supports peer-to-peer communication between browser-side endpoints by routing communication via the server in a way that avoids excessive serialisation. RouST guarantees communication safety for endpoint web applications written using STScript APIs.

We evaluate the expressiveness of STScript for modern web programming using several production-ready case studies deployed as web applications.

CCS Concepts: • **Software and its engineering** → **Source code generation**; • **Theory of computation** → *Distributed computing models*.

Keywords: TypeScript, WebSocket, API generation, session types, deadlock freedom, web programming

CC '21, March 2–3, 2021, Virtual, USA

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ACM Reference Format:

Anson Miu, Francisco Ferreira, Nobuko Yoshida, and Fangyi Zhou. 2021. Communication-Safe Web Programming in TypeScript with Routed Multiparty Session Types. In *Proceedings of the 30th ACM SIGPLAN International Conference on Compiler Construction (CC '21)*, March 2–3, 2021, Virtual, USA. ACM, New York, NY, USA, 27 pages. <https://doi.org/10.1145/3446804.3446854>

1 Introduction

Web technology advancements have changed the way people use computers. Many services that required standalone applications, such as email, chat, video conferences, or even games, are now provided in a browser. While the Hypertext Transfer Protocol (HTTP) is widely used for serving web pages, its Request-Response model limits the communication patterns — the server may not send data to a client without the client first making a request.

The *WebSocket Protocol* [12] addresses this limitation by providing a bi-directional channel between the client and the server, akin to a Unix socket. Managing the correct usage of WebSockets introduces an additional concern in the development process, due to a lack of WebSocket testing tools, requiring an (often ad-hoc) specification of the communication protocol between server and clients.

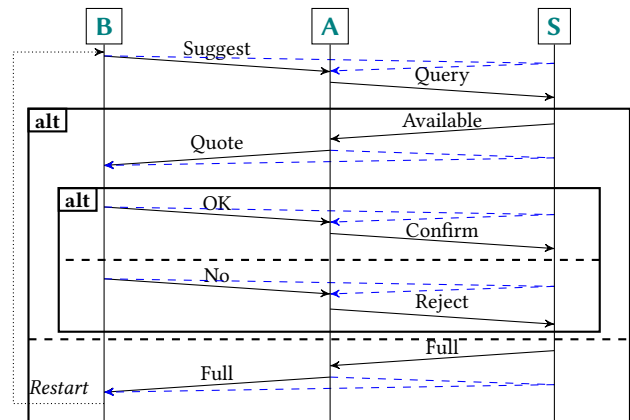


Figure 1. Travel Agency Protocol as a Sequence Diagram

Consider the scenario in Fig. 1, where an online travel agency operates a “travelling with a friend” scheme (ignoring

the blue dashed arrows). It starts when a traveller (**B**) suggests a trip destination to their friend (**A**), who then queries the travel agency (**S**) if the trip is available. If so, the friends discuss among themselves whether to accept or reject the quoted price. If the trip was unavailable, the friends start again with a new destination.

An implementation of the travel agency protocol may contain programming errors, risking *communication safety*. For example, the following implementation of the client-side endpoint for traveller **A** sending a quote to traveller **B**.

```

1 <input type='number' id='quote' />
2 <button id='submitQuote'>Send Quote to B</button>
3 <script>
4 document.getElementById('submitQuote')
5   .addEventListener('click', () => {
6     const quote = document.getElementById('quote').value;
7     travellerB.send({ label: 'quote', quote });
8     travellerB.onMessage( /* go to different screen */ );
9     /* ...snip... */ }); </script>

```

There are subtle errors that violate the communication protocol, but these bugs are unfortunately left for the developer to manually identify and test against:

Communication Mismatch Whilst the input field mandates a *numerical value* (Line 1) for the quote, the value from the input field is actually a string. If **B** expects a number and performs arithmetic operations on the received payload from **A**, the type mismatch may be left hidden due to implicit type coercion and cause unintended errors.

Channel Usage Violation As **B** may take time to respond, **A** can experience a delay between sending the quote and receiving a response. Notice that the button remains *active* after sending the quote — **A** could click on the button again, and send additional quotes (thus reusing the communication channel), but **B** may be unable to deal with extra messages.

Handling Session Cancellation An additional concern is how to handle browser disconnections, as both travellers can freely close their browsers at any stage of the protocol. Suppose **S** temporarily reserves a seat on **A**'s query. If **A** closes their browser, the developer would need to make sure that **A** notifies **S** prior to disconnecting, and **S** needs to implement recovery logic (e.g. releasing the reserved seat) accordingly.

To prevent these errors and ensure deadlock-freedom, we propose to apply *session types* [14, 15] into practical interactive web programming. The scenario described in Fig. 1 can be precisely described with a *global type* using the typing discipline of *multiparty session types* (MPST) [15]. Well-typed implementations conform to the given *global protocol*, are guaranteed free from communication errors *by construction*.

Whereas session type programming is well-studied [1], its application on web programming, in particular, interactive web applications, remains relatively unexplored. Integrating session types with web programming has been piloted by recent work [13, 20, 24], yet none are able to seamlessly implement the previous application scenario: Fowler [13]

uses *binary* (2-party) session types; and King et al. [20] require each non-server role to only communicate to the server, hence preventing interactions between non-server roles (cf. talking to a friend in the scenario). The programming languages used in these works are, respectively, Links [8] and PureScript [28], both not usually considered mainstream in the context of modern web programming. The Jolie language [24] focuses more on the server side, with limited support for an interactive front end of web applications.

This paper presents a novel toolchain, *Session TypeScript* (STScript), for implementing multiparty protocols safely in web programming. STScript integrates with *modern* tools and practices, utilising the popular programming language TypeScript, front end framework React.js and back end runtime Node.js. Developers first specify a multiparty protocol and we generate *correct-by-construction* APIs for developers to implement the protocol. The generated APIs use WebSocket to establish communication between participants, utilising its flexibility over the traditional HTTP model. When developers use our generated APIs to correctly implement the protocol endpoints, STScript guarantees the freedom from communication errors, including deadlocks, communication mismatches, channel usage violation or cancellation errors.

Our toolchain is backed by a new session theory, a *routed multiparty session types theory* (RouST), to endow servers with the capacity to *route messages* between web clients. The new theory addresses a practical limitation that WebSocket connections still require clients to connect to a prescribed server, constraining the ability for inter-client communication. To overcome this, our API *routes* inter-client messages through the server, improving the expressiveness over previous work and enabling developers to correctly implement multiparty protocols, as we show with blue dashed arrows in Fig. 1. In our travel agency scenario, the agency plays the server role: it will establish WebSocket channels with each participant, and be tasked with routing all the messages between the friends. We formalise this routing mechanism as RouST and prove deadlock-freedom of RouST and show a behaviour-preserving encoding from the original MPST to RouST. The formalism and results in RouST directly guide a deadlock-free protocol implementation in Node.js via the router, preserving communication structures of the original protocol written by a developer.

Finally, we evaluate our toolchain (STScript) by case studies. We evaluate the expressiveness by implementing a number of web applications, such as interactive multiplayer games (Noughts and Crosses, Battleship) and web services (Travel Agency) that require routed communication.

Contributions and Structure of the Paper. § 2 presents an overview of our toolchain STScript, which generates APIs for communication-safe web applications in TypeScript from multiparty protocol descriptions. § 3 motivates how the generated code executes the multiparty protocol descriptions,

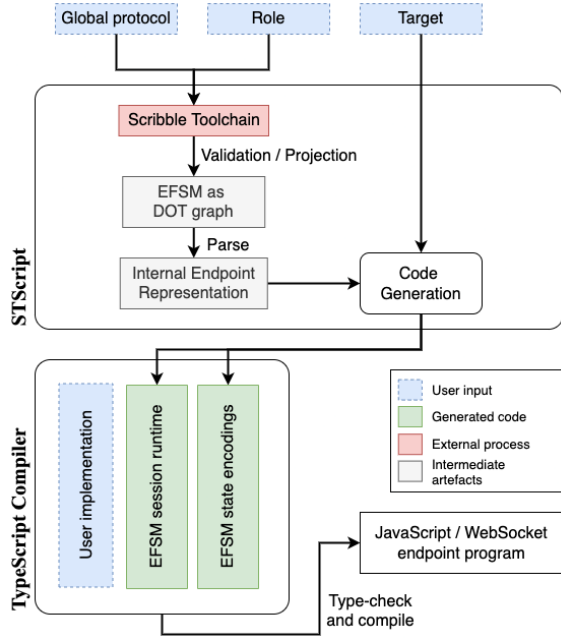


Figure 2. Overview of the toolchain STScript

and present how STScript prevents common errors in the context of web applications. § 4 presents RouST, multiparty session types (MPST) extended with *routing*, and define a trace-preserving encoding of the original MPST into RouST. § 5 evaluates our toolchain STScript via a case study of Noughts and Crosses and performance experiments. § 6 gives related and future work.

Appendix includes omitted code, definitions, performance benchmarks and detailed proofs. The artifact accompanying this paper [23] is available via DOI or at <https://github.com/STScript-2020/cc21-artifact>, containing the source code of STScript, with implemented case studies and performance benchmarks. See Appendix A for details about the artifact.

2 Overview

In this section, we give an overview of our code generation toolchain STScript (Fig. 2), demonstrate how to implement the travel agency scenario (Fig. 1) as a TypeScript web application, and explain how STScript prevents those errors.

Multiparty Session Type Design Workflow. Multiparty session types (MPST) [15] use a top-down design methodology (Fig. 3). Developers begin with *specifying* the global communication pattern of all participants in a *global type* or a *global protocol*. The protocol is described in the Scribble protocol description language [16, 31, 34]. We show the global protocol of the travel agency scenario (in § 1) in Fig. 4.

The Scribble language provides a user-friendly way to describe the global protocol in terms of a sequence of message exchanges between roles. A message is identified by its label (e.g. Suggest, Query, etc), and carries payloads (e.g. number, string, etc). The `choice` syntax (e.g. Line 4) describes possible branches of the protocol – in this case, the Server may

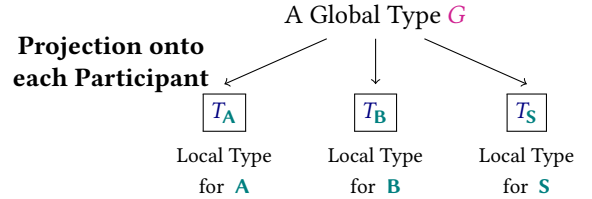


Figure 3. Top-down MPST Design Methodology

```

1 global protocol TravelAgency(role A, role B, role S)
2 { Suggest(string) from B to A; //friend suggests place
3   Query(string) from A to S;
4   choice at S
5     { Available(number) from S to A;
6       Quote(number) from A to B; //check price with friend
7       choice at B
8         { OK(number) from B to A;
9           Confirm(credentials) from A to S; }
10      or { No() from B to A;
11          Reject() from A to S; } }
12 or { Full() from S to A; Full() from A to B;
13     do TravelAgency(A, B, S); } }

```

Figure 4. Travel Agency Protocol in Scribble

respond to the query either with Available, so the customer continues booking, or with Full, so the customer retries by restarting the protocol via the `do` syntax (Line 13).

In this scenario, we designate the roles **A** and **B** as *client roles*, and role **S** as a *server role*. Participating endpoints can obtain their local views of the communication protocol, known as *local types*, via *projection* from the specified global type (Fig. 3). The local type of an endpoint can be then used in the code generation process, to generate APIs that are *correct by construction* [17, 20, 35].

The code generation toolchain STScript (Fig. 2) follows the MPST design philosophy. In STScript, we take the global protocol as inputs, and generate endpoint code for a given role as outputs, depending on the nature of the role. We use the Scribble toolchain for initial processing, and use an *endpoint finite state machine* (EFSM) based code generation technique targeting the TypeScript Language.

Targeting Web Programming. The TypeScript [2] programming language is used for web programming, with a static type system and a compiler to JavaScript. TypeScript programs follow a similar syntax to JavaScript, but may contain type annotations that are checked statically by the TypeScript type-checker. After type-checking, the compiler converts TypeScript programs into JavaScript programs, so they can be run in browsers and other hosts (e.g. Node.js).

To implement a wide variety of communication patterns, we use the *WebSocket* protocol [12], enabling bi-directional communication between the client and the server after connection. This contrasts with the traditional request-response model of HTTP, where the client needs to send a request and the server may only send a response after receiving the

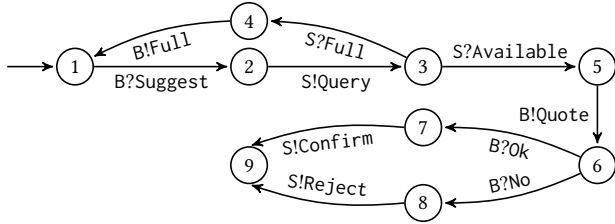


Figure 5. EFSM for TravelAgency role A

request. WebSockets require an endpoint to listen for connections and the other endpoint connecting. Moreover, clients, using the web application in a browser, may *only* start a connection to a WebSocket, and servers may *only* listen for new connections. The design of WebSocket limits the ability for two clients to communicate directly via a WebSocket (e.g. Line 2 in Fig. 4). STScript uses the server to *route* messages between client roles, enabling communication between all participants via a star network topology.

An important aspect of web programming is the interactivity of the user interface (UI). Viewed in a browser, the web application interacts with the user via UI events, e.g. mouse clicks on buttons. The handling of UI events may be implemented to send messages to the client (e.g. when the “Submit” button on the form is clicked), which may lead to practical problems. For instance, would clicking “Submit” button twice create two bookings for the customer? We use the popular *React.js* UI framework for generating client endpoints, and generate APIs that prevent such errors from happening.

Callback-Style API for Clients and Servers. Our code generation toolchain STScript produces TypeScript APIs in a *callback style* [35] to *statically* guarantee channel linearity. The input global protocol is analysed by the toolchain for well-formedness, and an *endpoint finite state machine* (EFSM) is produced for each endpoint. We show the EFSM for role A in Fig. 5. The states in the EFSM represent local types (subject to reductions) and transitions represent communication actions (Symbol ! stands for sending actions, ? for receiving).

In the callback API style, type signatures of callbacks are generated for transitions in the EFSM. Developers implement the callbacks to complete the program logic part of the application, whilst a generated *runtime* takes care of the communication aspects. For callbacks, sending actions correspond to callbacks prompting the payload type as a *return type*, so that the returned value can be sent by the runtime. Dually, receiving actions correspond to callbacks taking the payload type as an *argument*, so that the runtime invokes the callback with the received value.

Implementing the Server Role. In the travel agency protocol, as shown in Fig. 4, we designate role S as the server role. The server role does not only interact with the two clients, but also *routes* messages for the two clients. The routing will be handled automatically by the runtime, saving the need for developers to specify manually. As a result, the developer only handles the program logic regarding the

```

15 const agencyProvider = (sessionID: string) => {
16   const handleQuery = Session.Initial({
17     Query: async (Next, destination) => {
18       const response = await checkAvailability(sessionID, destination);
19       if (response.status === "available") {
20         return Next;
21       }
22     }
23   });
24   (property) Available: {
25     (payload: [number], generateSuccessor: (N
26     ext: (handler: Handler.S41) => State.S41)
27     => State.S41): State.S40;
28     (payload: [number], succ: State.S41): Sta
29     te.S40;
30   }
31 }
    
```

Figure 6. IDE Auto-Completion for Successor State

server, in this use case, namely providing quotes for holiday bookings and handling booking confirmations.

```

1 import { Session, S } from "./TravelAgency/S";
2 const agencyProvider = (sessionID: string) => {
3   const handleQuery = Session.Initial({
4     Query: async (Next, dest) => {
5       // Provide quotes for holiday bookings
6       const res = await checkAvailability(sessionID, dest);
7       if (res.status === "available") {
8         return Next.Available([res.quote], Next => ...);
9       } else { return Next.Full([], handleQuery); } }, });
10  return handleQuery; };
    
```

All callbacks carry an extra parameter, Next, which acts as a *factory function* for constructing the successor state. This empowers IDEs to provide auto-completion for developers. For example, the factory function provided by the callback for handling a Query message (Line 4) prompts the permitted labels in the successor send state, as illustrated in Fig. 6.

Implementing the Client Roles. To implement client roles, merely implementing the callbacks for the program logic is not sufficient — unlike servers, web applications have interactive user interfaces, additional to program logic. As mentioned previously, our code generation toolchain targets *React.js* for client roles. For background, the smallest building blocks in *React.js* are *components*, which can carry *properties* (immutable upon construction) and *states* (mutable). Components are *rendered* into HTML elements, and they are re-rendered when the component state mutates.

To bind the program logic with an interactive user interface, we provide *component factories* that allow the UI component to be interposed with the current state of the EFSM. Developers can provide the UI event handler to the component factory, and obtain a component for rendering. The generate code structure enforces that the state transition strictly follows the EFSM, so programmer errors (such as the double “submit” problem) are prevented by design.

```

1 render() {
2   const OK = this.OK('onClick', () => [this.state.split]);
3   const NO = this.No('onClick', () => []);
4   return (...
5     <NO><Button color='secondary'>No</Button></NO>
6     <OK><Button color='primary'>OK</Button></OK> ...); }
    
```


Using the send state component in the FSM for the endpoint **B** as an example, Line 2 reads, “generate a React component that sends the OK message with `this.state.split` as payload on a click event”. It is used on Line 6 as a wrapper for a stylised `<Button>` component. The runtime invokes the handler and performs the state transition, which prevents the double “submit” problem by design.

Guaranteeing Communication Safety. Returning to the implementation in § 1, we outline how STScript prevents common errors to enable type-safe web programming.

Communication Mismatch All generated callbacks are typed according to the permitted payload data type specified in the protocol, making it impossible for traveller **A** to send the quote as a string by accident.

Channel Usage Violation The generated client-side runtime requires the developer to provide different UI components for each EFSM state – once traveller **A** submits a quote, the runtime will transition to, thus render the component of, a different EFSM state. This guarantees that, whilst waiting for a response from traveller **B**, it is impossible for traveller **A** to submit another quote and violate channel linearity.

Handling Session Cancellation If either traveller closes their browser before the protocol runs to completion, the generated runtimes leverage the events available on their WebSocket connections to notify (via the server) other roles about the session cancellation. The travel agency can implement the error handler callback (generated by STScript) to perform clean-up logic in response to cancellations.

3 Implementation

In this section, we explain how the generated code executes the EFSM for Node.js and React.js targets. We also present how STScript APIs handle errors in a dynamic web-based environment (for complete code, see Appendix E).

Session Runtime. The session runtime executes the EFSM in a manner permitted by the multiparty protocol description. The runtime keeps track of the current state, performs the required communication action (i.e. send or receive a message), and transitions to the successor state. The runtime provides *seams* for the developer to inject the callback implementations, which define application-specific concerns for the EFSM, such as what message payload to send (and dually, how to process a received message). This design conceals the WebSocket APIs from the developer and entails that the developer cannot trigger a send or receive action, so STScript can *statically* guarantee protocol conformance.

Executing the EFSM in Node.js. Each state of the EFSM is characterised by a (generated) `State` class and a type describing the shape of the callback (supplied by the developer). To allow the server to correctly manage concurrent sessions, the developer can access a (generated) *session ID* when implementing the callbacks. STScript also generates *IO interfaces*

for each kind of EFSM state – send, receive, or terminal. The generated `State` class implements the interface corresponding to the type of communication action it performs.

```

1 next(state: State.Type) {
2   switch (state.type) {
3     case 'Send': return state.performSend(
4       this.next, this.cancel, this.send);
5     case 'Receive': return state.prepareReceive(
6       this.next, this.cancel, this.registerMessageHandler);
7     case 'Terminal': return; }}

```

The session runtime for Node.js is a class that executes the EFSM using a *state transition function* parameterised by the `State` class of the current EFSM state. As the IO interfaces constitute a *discriminated union*, the runtime can parse the type of the current EFSM state and propagate the appropriate IO functions (for sending or receiving) to the `State` class. In turn, the `State` class invokes the callback supplied by the developer to inject program logic into the EFSM, perform the communication action (using `this.send` or `this.registerMessageHandler`), and invoke the state transition function (`this.next`) with the successor state.

Notably, the routed messages are completely absent because the generated code transparently routes messages without exposing any details. As messages specify their intended recipient, the runtime identifies messages not intended for the server by inspecting the metadata, and forwards them to the WebSocket connected to the intended recipient.

Executing the EFSM in React.js. Each state in the EFSM is encoded as an *abstract* React component. The developer implements the EFSM by extending the abstract classes to provide their own implementation – namely, to build their user interface. Components for send states can access *component factories* to generate React components that perform a send action when a UI event (e.g. `onClick`, `onMouseOver`) is triggered. Components for receive states must implement abstract methods to handle all possible incoming messages.

The session runtime for React.js is a React component, instantiated using the developer’s implementation of each EFSM state. Channel communications are managed by the runtime, so the developer’s implementations cannot access the WebSocket APIs, which prevents channel reuse by construction. The runtime renders the component of the current EFSM state and binds the permitted communication action through supplying component properties.

Error Handling. An error handling mechanism is critical for web applications. Clients can disconnect from the session due to network connectivity issues or simply by closing the browser. Similarly, servers may also face connectivity issues.

Upon instantiating the session runtime, STScript requires developers to supply a *cancellation handler* to handle *local exceptions* (e.g. errors thrown by application logic) and *global session cancellations* (e.g. disconnection events by another

endpoint). The session runtime detects cancellation by listening to the *close event* on the WebSocket connection, and invokes the cancellation handler with appropriate arguments on a premature close event. We parameterise the cancellation handlers with additional information (e.g. which role disconnected from the session, the reason for the disconnection) to let developers be more specific in their error handling logic.

Cancellation Handlers for Servers. Server endpoints define cancellation handlers through a function, parameterised by the *session ID*, the *role* which initiated the cancellation, and (optionally) the *reason* for the cancellation — if the server-side logic throws an exception, the handler can access the thrown error through the reason parameter.

```

1  const handleCancel = async (sessionID, role, reason) => {
2    if (role === Role.Self) {
3      console.error(`${sessionID}: internal server error`); }
4    else { await tryRelease(sessionID); };
5    // Instantiate session runtime
6    new S(wss, handleCancel, agencyProvider);

```

Using the Travel Agency scenario introduced in § 1, if the customer prematurely closes their browser before responding to a Quote, the server can detect this (Line 4) and release the reservation to preserve data integrity.

Cancellation Handlers for Clients. Browser-side endpoints also define cancellation handlers through a function parameterised in the same way as those in Node.js, but must return a React component to be rendered by the session runtime. In the context of the Travel Agency scenario, the customer can render a different UI depending on whether the server disconnected or their friend closed their web browser prematurely. Browser endpoints can also respond to cancellations emitted by other client-side roles: when a browser endpoint disconnects, the server detects this and propagates the cancellation to the other client-side roles.

4 RouST: Routed Session Types

This section defines the syntax and semantics of RouST and proves some important properties. We show the sound and complete trace correspondence between a global type and a collection of endpoint types projected from the global type (Theorem 4.6). Using this result, we prove deadlock freedom (Theorem 4.7). We then show that, in spite of the added routed communications, RouST does not over-serialise communications by proving *communication preservations* between the original MPST and RouST (Theorem 4.11). These three theorems ensure that STScript endpoint programs are communication-safe, always make progress, and correctly conforms to the user-specified protocol.

4.1 Syntax of Routed Multiparty Session Types

We define the syntax of *global types* G and *local types* (or *endpoint types*) T in Definition 4.1. Global types are also known

as *protocols* and describe the communication behaviour between all participating roles (participants), while local types describe the behaviour of a single participating role. We shade additions to the original (or *canonical*) multiparty session type (MPST) [9, 11, 15, 30] in this colour .

Definition 4.1 (Global and Local Types). The syntax of *global* and *local types* are defined below:

$$\begin{aligned}
 G ::= & \text{end} \mid \mathbf{t} \mid \mu t.G & T ::= & \text{end} \mid \mathbf{t} \mid \mu t.T \mid \mathbf{p} \hookrightarrow \mathbf{q} : \{l_i : T_i\}_{i \in I} \\
 & \mid \mathbf{p} \rightarrow \mathbf{q} : \{l_i : G_i\}_{i \in I} & & \mid \mathbf{p} \oplus \{l_i : T_i\}_{i \in I} \mid \mathbf{p} \oplus (\mathbf{q}) \{l_i : T_i\}_{i \in I} \\
 & \mid \mathbf{p} \dashv \mathbf{s} \rightarrow \mathbf{q} : \{l_i : G_i\}_{i \in I} & & \mid \mathbf{p} \& \{l_i : T_i\}_{i \in I} \mid \mathbf{p} \& (\mathbf{q}) \{l_i : T_i\}_{i \in I}
 \end{aligned}$$

Global Types. $\mathbf{p} \rightarrow \mathbf{q} : \{l_i : G_i\}_{i \in I}$ describes a *direct communication* of a message l_i from a role \mathbf{p} to \mathbf{q} . We require that $\mathbf{p} \neq \mathbf{q}$, that labels l_i are pairwise distinct, and that the index set I is not empty. The message in the communication can carry a label among a set of permitted labels l_i and some payload. After a message with label l_i is received by \mathbf{q} , the communication continues with G_i , according to the chosen label. For simplicity, we do not include payload types (integers, strings, booleans, etc) in the syntax. We write $\mathbf{p} \rightarrow \mathbf{q} : l : G$ for single branches. For recursion, we adopt an *equi-recursive* view [27, §21], and use $\mu t.G$ and \mathbf{t} for a *recursive protocol* and a *type variable*. We require that recursive types are *contractive* (*guarded*), i.e. the recursive type $\mu t.G$ progresses after the substitution $G[\mu t.G/t]$, prohibiting types such as $\mu t.t$. We use **end** to mark the *termination* of the protocol, and often omit the final **end**.

To support routed communication, we allow messages to be sent through a *router role*. A *routed communication* $\mathbf{p} \dashv \mathbf{s} \rightarrow \mathbf{q} : \{l_i : G_i\}_{i \in I}$ describes a router role \mathbf{s} coordinating the communication of a message from \mathbf{p} to \mathbf{q} : \mathbf{q} offers \mathbf{p} a choice in the index set I , but \mathbf{p} sends the selected choice l_i to the router \mathbf{s} instead. The router *forwards* the selection from \mathbf{p} to \mathbf{q} . After \mathbf{q} receives \mathbf{p} 's selection, the communication continues with G_i . \mathbf{s} ranges over the set of roles $\mathbf{p}, \mathbf{q}, \dots$, but we use \mathbf{s} by convention as the router is usually some server. The syntax for routed communication shares the same properties as direct communication, but we additionally require that $\mathbf{p} \neq \mathbf{q} \neq \mathbf{s}$. We use $\text{pt}(G)$ to denote the set of participants in the global type G .

Example 4.2 (Travel Agency). The travel agency protocol, as shown in Fig. 4, is described by the global type G_{travel} in the original MPST, and G_{travel}^R in RouST.

$$\begin{aligned}
 G_{\text{travel}} = & \mu t. \mathbf{B} \rightarrow \mathbf{A} : \text{Suggest} . \mathbf{A} \rightarrow \mathbf{S} : \text{Query} . \\
 & \left. \begin{array}{l} \text{Available :} \\ \mathbf{A} \rightarrow \mathbf{B} : \text{Quote} . \mathbf{B} \rightarrow \mathbf{A} : \\ \left\{ \begin{array}{l} \text{OK : } \mathbf{A} \rightarrow \mathbf{S} : \text{Confirm} \\ \text{No : } \mathbf{A} \rightarrow \mathbf{S} : \text{Reject} \end{array} \right\} \\ \text{Full : } \mathbf{A} \rightarrow \mathbf{B} : \text{Full} . \mathbf{t} \end{array} \right\} \\
 G_{\text{travel}}^R = & \mu t. \mathbf{B} \dashv \mathbf{S} \rightarrow \mathbf{A} : \text{Suggest} . \mathbf{A} \rightarrow \mathbf{S} : \text{Query} . \\
 & \left. \begin{array}{l} \text{Available :} \\ \mathbf{A} \dashv \mathbf{S} \rightarrow \mathbf{B} : \text{Quote} . \mathbf{B} \dashv \mathbf{S} \rightarrow \mathbf{A} : \\ \left\{ \begin{array}{l} \text{OK : } \mathbf{A} \rightarrow \mathbf{S} : \text{Confirm} \\ \text{No : } \mathbf{A} \rightarrow \mathbf{S} : \text{Reject} \end{array} \right\} \\ \text{Full : } \mathbf{A} \dashv \mathbf{S} \rightarrow \mathbf{B} : \text{Full} . \mathbf{t} \end{array} \right\}
 \end{aligned}$$

Local Types. We first describe the local types in the original MPST theory. $\mathbf{q} \& \{l_i : T_i\}_{i \in I}$ stands for **branching** and $\mathbf{q} \oplus \{l_i : T_i\}_{i \in I}$ stands for **selection**. From the perspective of \mathbf{p} , branching (resp. selection) offers (resp. selects) a choice among an index set I to (resp. from) \mathbf{q} , and communication continues with the corresponding T_i . Local types $\mu t. T$, \mathbf{t} and **end** have the same meaning as their global type counterparts.

We add new syntax to express routed communication from the perspective of each role involved. The local type $\mathbf{p} \& \langle s \rangle \{l_i : T_i\}_{i \in I}$ is a **routed branching**: the current role is offering a choice from an index set I to \mathbf{p} (the intended sender), but expects to receive \mathbf{p} 's choice via the router role \mathbf{s} ; if the message received is labelled l_i , \mathbf{q} will continue with local type T_i . The local type $\mathbf{q} \oplus \langle s \rangle \{l_i : T_i\}_{i \in I}$ is a **routed selection**: the current role makes a selection from an index set I to \mathbf{q} (the intended recipient), but sends the selection to the router role \mathbf{s} ; if the message sent is labelled l_i , \mathbf{p} will continue with local type T_i . The local type $\mathbf{p} \hookrightarrow \mathbf{q} : \{l_i : T_i\}_{i \in I}$ is a **routing communication**. The router role orchestrates the communication from \mathbf{p} to \mathbf{q} , and continues with local type T_i depending on the label of the forwarded message. We keep track of the router role to distinguish between routing communications from normal selection and branching interactions.

Endpoint Projection. The local type T of a participant \mathbf{p} in a global type G is obtained by the *endpoint projection* of G onto \mathbf{p} , denoted by $G \upharpoonright \mathbf{p}$.

Definition 4.3 (Projection). The projection of G onto \mathbf{r} , written $G \upharpoonright \mathbf{r}$ is defined as:

$$\begin{aligned}
 & (\mathbf{p} \rightarrow \mathbf{q} : \{l_i : G_i\}_{i \in I}) \upharpoonright \mathbf{r} & (\mu t. G) \upharpoonright \mathbf{r} \\
 = & \begin{cases} \mathbf{q} \oplus \langle s \rangle \{l_i : G_i \upharpoonright \mathbf{r}\}_{i \in I} & \text{if } \mathbf{r} = \mathbf{p} \\ \mathbf{p} \& \langle s \rangle \{l_i : G_i \upharpoonright \mathbf{r}\}_{i \in I} & \text{if } \mathbf{r} = \mathbf{q} \\ \mathbf{p} \hookrightarrow \mathbf{q} : \{l_i : G_i \upharpoonright \mathbf{r}\}_{i \in I} & \text{if } \mathbf{r} = \mathbf{s} \\ \prod_{i \in I} G_i \upharpoonright \mathbf{r} & \text{otherwise} \end{cases} & = \begin{cases} \mu t. (G \upharpoonright \mathbf{r}) & \text{if } G \upharpoonright \mathbf{r} \neq \mathbf{t} \\ \mathbf{end} & \text{otherwise} \end{cases} \\
 & \quad \quad \quad \mathbf{end} \upharpoonright \mathbf{r} = \mathbf{end} & \quad \quad \quad \mathbf{t} \upharpoonright \mathbf{r} = \mathbf{t}
 \end{aligned}$$

The projection $(\mathbf{p} \rightarrow \mathbf{q} : \{l_i : G_i\}_{i \in I}) \upharpoonright \mathbf{r}$ is defined similar to $(\mathbf{p} \rightarrow \mathbf{q} : \{l_i : G_i\}_{i \in I}) \upharpoonright \mathbf{r}$ dropping \mathbf{s} (in the resulting local type) and the third case.

A *merge operator* (\sqcap) is used when projecting a communication onto a non-participant. It checks that the projections of all continuations must be “compatible” (see Definition B.2).

Example 4.4 (Merging Local Types). Two branching types from the same role with disjoint labels can be merged into a type carrying both labels, e.g. $\mathbf{A} \& \text{Hello}.\mathbf{end} \sqcap \mathbf{A} \& \text{Bye}.\mathbf{end} = \mathbf{A} \& \{\text{Hello} : \mathbf{end}; \text{Bye} : \mathbf{end}\}$. The same is not true for selections, $\mathbf{A} \oplus \text{Hello}.\mathbf{end} \sqcap \mathbf{A} \oplus \text{Bye}.\mathbf{end}$ is undefined.

$$\begin{aligned}
 G_1 &= \mathbf{A} \rightarrow \mathbf{B} : \left\{ \begin{array}{l} \text{Greet} : \mathbf{A} \rightarrow \mathbf{C} : \text{Hello} . \mathbf{end} \\ \text{Farewell} : \mathbf{A} \rightarrow \mathbf{C} : \text{Bye} . \mathbf{end} \end{array} \right\} \\
 G_2 &= \mathbf{A} \rightarrow \mathbf{B} : \left\{ \begin{array}{l} \text{Greet} : \mathbf{C} \rightarrow \mathbf{A} : \text{Hello} . \mathbf{end} \\ \text{Farewell} : \mathbf{C} \rightarrow \mathbf{A} : \text{Bye} . \mathbf{end} \end{array} \right\}
 \end{aligned}$$

The global type G_1 can be projected to role \mathbf{C} , but not G_2 .

Well-formedness. In the original theory, a global type G is *well-formed* (or *realisable*), denoted $\text{wellFormed}(G)$, if the projection is defined for all its participants.

$$\text{wellFormed}(G) \stackrel{\text{def}}{=} \forall \mathbf{p} \in \text{pt}(G). G \upharpoonright \mathbf{p} \text{ exists}$$

We assume that the global type G is contractive (guarded).

In RouST, we say that a global type is well-formed *with respect to the role \mathbf{s} acting as the router*. We define the characteristics that \mathbf{s} must display in G to prove that it is a router, and formalise this as an *inductive relation*, $G \otimes \mathbf{s}$ (Definition 4.5), which reads \mathbf{s} is a *centroid in G* . The intuition is that \mathbf{s} is at the centre of all communication interactions.

Definition 4.5 (Centroid). The relation $G \otimes \mathbf{s}$ (\mathbf{s} is the centroid of G) is defined by the two axioms $\mathbf{end} \otimes \mathbf{s}$ and $\mathbf{t} \otimes \mathbf{s}$ and by the following rules:

$$\frac{G \otimes \mathbf{s} \quad \mathbf{s} \in \{\mathbf{p}, \mathbf{q}\} \quad \forall i \in I. G_i \otimes \mathbf{s} \quad \mathbf{r} = \mathbf{s} \quad \forall i \in I. G_i \otimes \mathbf{s}}{\mu t. G \otimes \mathbf{s} \quad \mathbf{p} \rightarrow \mathbf{q} : \{l_i : G_i\}_{i \in I} \otimes \mathbf{s} \quad \mathbf{p} \rightarrow \mathbf{r} \rightarrow \mathbf{q} : \{l_i : G_i\}_{i \in I} \otimes \mathbf{s}}$$

For direct communication, \mathbf{s} must be a participant and a centroid of all continuations. For routed communication, \mathbf{s} must be the router and be a centroid of all continuations. Now we define of well-formedness of a global type G in RouST with respect to the router \mathbf{s} (denoted $\text{wellFormed}^R(G, \mathbf{s})$):

$$\text{wellFormed}^R(G, \mathbf{s}) \stackrel{\text{def}}{=} (\forall \mathbf{p} \in \text{pt}(G). G \upharpoonright \mathbf{p} \text{ exists}) \wedge G \otimes \mathbf{s}$$

4.2 Semantics of RouST

This subsection defines the labelled transition system (LTS) over global types for RouST, building upon [11].

First, we define the labels (actions) in the LTS which distinguish the *direct* sending (and reception) of a message from the sending (and reception) of a message *via* an intermediate routing endpoint. Labels range over l, l', \dots are defined by:

$$l ::= \mathbf{pq}!j \mid \mathbf{pq}?j \mid \text{via}\langle \mathbf{s} \rangle(\mathbf{pq}!j) \mid \text{via}\langle \mathbf{s} \rangle(\mathbf{pq}?j)$$

The label $\text{via}\langle \mathbf{s} \rangle(\mathbf{pq}!j)$ represents the *sending* (performed by \mathbf{p}) of a message labelled j to \mathbf{q} through the intermediate router \mathbf{s} . The label $\text{via}\langle \mathbf{s} \rangle(\mathbf{pq}?j)$ represents the *reception* (initiated by \mathbf{q}) of a message labelled j send from \mathbf{p} through the intermediate router \mathbf{s} . The *subject* of a label l , denoted by $\text{subj}(l)$, is defined as: $\text{subj}(\text{via}\langle \mathbf{s} \rangle(\mathbf{pq}!j)) = \text{subj}(\mathbf{pq}!j) = \mathbf{p}$; and $\text{subj}(\text{via}\langle \mathbf{s} \rangle(\mathbf{pq}?j)) = \text{subj}(\mathbf{pq}?j) = \mathbf{q}$.

LTS Semantics over Global Types. The LTS semantics model *asynchronous communication* to reflect our implementation. We introduce intermediate states (i.e. messages in transit) within the grammar of global types: the construct $\mathbf{p} \rightsquigarrow \mathbf{q} : j : \{l_i : G_i\}_{i \in I}$ represents that the message l_j has been sent by \mathbf{p} but not yet received by \mathbf{q} ; and the construct $\mathbf{p} \rightsquigarrow_s \mathbf{q} : j : \{l_i : G_i\}_{i \in I}$ represents that l_j has been sent from \mathbf{p} to the router \mathbf{s} but not yet routed to \mathbf{q} . We define the LTS semantics over global types, denoted by $G \xrightarrow{l} G'$, in Fig. 7. [GR1] and [GR2] model the emission and reception of a message; [GR3] models recursions; [GR4] and [GR5] model causally unrelated transmissions – we only enforce the syntactic order of messages for the participants involved

$$\begin{array}{c}
\frac{}{\mathbf{p} \rightarrow \mathbf{q} : \{l_i : G_i\}_{i \in I} \xrightarrow{\text{pq}!j} \mathbf{p} \rightsquigarrow \mathbf{q} . j : \{l_i : G_i\}_{i \in I}} \text{[GR1]} \quad \frac{}{\mathbf{p} -s \rightarrow \mathbf{q} : \{l_i : G_i\}_{i \in I} \xrightarrow{\text{via}(s)(\text{pq}!j)} \mathbf{p} \rightsquigarrow_s \mathbf{q} . j : \{l_i : G_i\}_{i \in I}} \text{[GR6]} \\
\frac{}{\mathbf{p} \rightsquigarrow \mathbf{q} . j : \{l_i : G_i\}_{i \in I} \xrightarrow{\text{pq}^?j} G_j} \text{[GR2]} \quad \frac{G[\mu t.G/t] \xrightarrow{l} G'}{\mu t.G \xrightarrow{l} G'} \text{[GR3]} \quad \frac{}{\mathbf{p} \rightsquigarrow_s \mathbf{q} . j : \{l_i : G_i\}_{i \in I} \xrightarrow{\text{via}(s)(\text{pq}^?j)} G_j} \text{[GR7]} \\
\frac{\forall i \in I. G_i \xrightarrow{l} G'_i \quad \text{subj}(l) \notin \{\mathbf{p}, \mathbf{q}\}}{\mathbf{p} \rightarrow \mathbf{q} : \{l_i : G_i\}_{i \in I} \xrightarrow{l} \mathbf{p} \rightarrow \mathbf{q} : \{l_i : G'_i\}_{i \in I}} \text{[GR4]} \quad \frac{\forall i \in I. G_i \xrightarrow{l} G'_i \quad \text{subj}(l) \notin \{\mathbf{p}, \mathbf{q}\}}{\mathbf{p} -s \rightarrow \mathbf{q} : \{l_i : G_i\}_{i \in I} \xrightarrow{l} \mathbf{p} -s \rightarrow \mathbf{q} : \{l_i : G'_i\}_{i \in I}} \text{[GR8]} \\
\frac{G_j \xrightarrow{l} G'_j \quad \text{subj}(l) \neq \mathbf{q} \quad \forall i \in I \setminus \{j\}. G'_i = G_i}{\mathbf{p} \rightsquigarrow \mathbf{q} . j : \{l_i : G_i\}_{i \in I} \xrightarrow{l} \mathbf{p} \rightsquigarrow \mathbf{q} . j : \{l_i : G'_i\}_{i \in I}} \text{[GR5]} \quad \frac{G_j \xrightarrow{l} G'_j \quad \text{subj}(l) \neq \mathbf{q} \quad \forall i \in I \setminus \{j\}. G'_i = G_i}{\mathbf{p} \rightsquigarrow_s \mathbf{q} . j : \{l_i : G_i\}_{i \in I} \xrightarrow{l} \mathbf{p} \rightsquigarrow_s \mathbf{q} . j : \{l_i : G'_i\}_{i \in I}} \text{[GR9]}
\end{array}$$

Figure 7. LTS over Global Types in RouST

in the action l . [GR6] and [GR7] are analogous to [GR1] and [GR2] for describing routed communication, but uses the “routed in-transit” construct instead. [GR8] and [GR9] are analogous to [GR4] and [GR5]. An important observation from [GR8] and [GR9] is that, for the router, the syntactic order of routed communication can be freely interleaved between the syntactic order of direct communication. This is crucial to ensure that the router does not over-serialise communication. See Example 4.13 for an LTS example.

Relating Semantics of Global and Local Types. We prove the soundness and completeness of our LTS semantics with respect to projection. We take three steps following [11]:

1. We extend the LTS semantics with *configuration* (\vec{T}, \vec{w}) , a collection of local types \vec{T} with FIFO queues between each pair of participants \vec{w} .
2. We extend the definition of projection, to obtain a configuration of a global type (a *projected configuration*), which expresses intermediate communication over FIFO queues.
3. We prove the trace equivalence between the global type and its projected configuration (i.e. the *initial configuration of G* , $(\vec{T}, \vec{\epsilon})$, where $\vec{T} = \{G \upharpoonright \mathbf{p}\}_{\mathbf{p} \in \mathcal{P}}$ are a set of local types projected from G and ϵ is an empty queue).

The proof is non-trivial: due to space limitations, we omit the semantics of local types, configurations and global configurations, and only state the main result (see Appendices B and C).

Theorem 4.6 (Sound and Complete Trace Equivalence). *Let G be a well-formed canonical global type. Then G is trace equivalent to its initial configuration.*

Theorem 4.7 proves traces specified by a well-formed global protocol are *deadlock-free*, i.e. the global type either completes all communications, or otherwise makes progress. Note that this theorem implies the deadlock-freedom of configurations by Theorem 4.6.

Theorem 4.7 (Deadlock Freedom). *Let G be a global type. Suppose G is well-formed with respect to some router s , i.e.*

$\text{wellFormed}^R(G, s)$. Then we have:

$$\forall G'. \left(G \rightarrow^* G' \implies (G' = \text{end}) \vee \exists G'', l. (G' \xrightarrow{l} G'') \right)$$

4.3 From Canonical MPST to RouST

We present an encoding from the canonical MPST theory (no routers) to RouST. This encoding is *parameterised* by the router role (conventionally denoted as s); the intuition is that we encode all communication interactions to involve s . If the encoding preserves the semantics of the canonical global type, then this encoding can guide a correct protocol implementation in Node.js via s , preserving communication structures of the original protocol without deadlock.

Router-Parameterised Encoding. We define the router-parameterised encoding on global types, local types and LTS labels in the MPST theory. We start with global types, as presented in Definition 4.8. The main rule is the direct communication: if the communication did not go through s , then the encoded communication involves s as the router.

Definition 4.8 (Encoding on Global Types). The encoding of global type G with respect to the router role s , denoted by $\llbracket G, s \rrbracket$, is defined as:

$$\begin{aligned}
\llbracket \text{end}, s \rrbracket &= \text{end} & \llbracket t, s \rrbracket &= t & \llbracket \mu t.G, s \rrbracket &= \mu t. \llbracket G, s \rrbracket \\
\llbracket \mathbf{p} \rightarrow \mathbf{q} : \{l_i : G_i\}_{i \in I}, s \rrbracket &= \begin{cases} \mathbf{p} \rightarrow \mathbf{q} : \{l_i : \llbracket G_i, s \rrbracket\}_{i \in I} & \text{if } s \in \{\mathbf{p}, \mathbf{q}\} \\ \mathbf{p} -s \rightarrow \mathbf{q} : \{l_i : \llbracket G_i, s \rrbracket\}_{i \in I} & \text{otherwise} \end{cases}
\end{aligned}$$

Local types express communication from the perspective of a particular role, hence the encoding takes two roles.

Definition 4.9 (Encoding on Local Types). The encoding of local type T (from the perspective of role \mathbf{q}) with respect to the router role s , denoted by $\llbracket T, \mathbf{q}, s \rrbracket$, is defined as:

$$\begin{aligned}
\llbracket \text{end}, \mathbf{q}, s \rrbracket &= \text{end} & \llbracket t, \mathbf{q}, s \rrbracket &= t & \llbracket \mu t.T, \mathbf{q}, s \rrbracket &= \mu t. \llbracket T, \mathbf{q}, s \rrbracket \\
\llbracket \mathbf{p} \oplus \{l_i : T_i\}_{i \in I}, \mathbf{q}, s \rrbracket &= \begin{cases} \mathbf{p} \oplus \{l_i : \llbracket T_i, \mathbf{q}, s \rrbracket\}_{i \in I} & \text{if } s \in \{\mathbf{p}, \mathbf{q}\} \\ \mathbf{p} \oplus (s) \{l_i : \llbracket T_i, \mathbf{q}, s \rrbracket\}_{i \in I} & \text{otherwise} \end{cases} \\
\llbracket \mathbf{p} \& \{l_i : T_i\}_{i \in I}, \mathbf{q}, s \rrbracket &= \begin{cases} \mathbf{p} \& \{l_i : \llbracket T_i, \mathbf{q}, s \rrbracket\}_{i \in I} & \text{if } s \in \{\mathbf{p}, \mathbf{q}\} \\ \mathbf{p} \& (s) \{l_i : \llbracket T_i, \mathbf{q}, s \rrbracket\}_{i \in I} & \text{otherwise} \end{cases}
\end{aligned}$$

Lemma 4.10 (Correspondence between Encodings). *The projection of an encoded global type $\llbracket G, s \rrbracket \uparrow r$ is equal to the encoded local type after projection $\llbracket G \uparrow r, r, s \rrbracket$, with respect to router s , i.e. $\forall r, s, G. (r \neq s \implies \llbracket G, s \rrbracket \uparrow r = \llbracket G \uparrow r, r, s \rrbracket)$.*

The constraint $r \neq s$ is necessary because we would otherwise lose information on the right-hand side of the equality: the projection of s in the original communication does not contain the routed interactions, so applying the local type encoding cannot recover this information.

Theorem 4.11 (Encoding Preserves Well-Formedness). *Let G be a global type, and s be a role. Then we have:*

$$\text{wellFormed}(G) \iff \text{wellFormed}^R(\llbracket G, s \rrbracket)$$

Preserving Communication. We present a crucial result that directly addresses the pitfalls of naive definitions of routed communication – our encoding does not over-serialise the original communication. We prove that our encoding preserves the LTS semantics over global types – or more precisely, we can use the encodings over global types and LTS actions to encode all possible transitions in the LTS for global types in the canonical MPST theory. We define the encoding of label l in the original MPST as: $\llbracket pq!j, s \rrbracket = \text{via}(s)(pq!j)$ and $\llbracket pq?j, s \rrbracket = \text{via}(s)(pq?j)$ if $s \notin \{p, q\}$ and otherwise $\llbracket l, s \rrbracket = l$.

Theorem 4.12 (Encoding Preserves Semantics). *Let G, G' be well-formed global types such that $G \xrightarrow{l} G'$ for some label l . Then we have:*

$$\forall l, s. \left(G \xrightarrow{l} G' \iff \llbracket G, s \rrbracket \xrightarrow{\llbracket l, s \rrbracket} \llbracket G', s \rrbracket \right)$$

We conclude with an example which demonstrates global semantics in RouST and a use of the encoding.

Example 4.13 (Encoding Preserves Semantics). Consider the global type

$$G = p \rightarrow q : M1 . s \rightarrow q : M2 . \text{end.}$$

We apply our encoding with respect to the router role s :

$$\llbracket G, s \rrbracket = p \rightarrow s \rightarrow q : M1 . s \rightarrow q : M2 . \text{end.}$$

We note that $l = sq!M2$ can reduce G through [GR1] (via one application of [GR4]). After encoding, we have that $\llbracket l, s \rrbracket = l$. The encoded global type $\llbracket G, s \rrbracket$ can be reduced by l through [GR1] (via one application of [GR8]), as demonstrated by Theorem 4.12. The label $l = sq!M2$ is a prefix of a valid execution trace for G , given below.

$$G \xrightarrow{sq!M2} p \rightarrow q : M1 \xrightarrow{pq!M1} p \rightarrow q : M2 \xrightarrow{sq?M2} \text{end}$$

Interested readers can verify that the encoded trace (given below) is a valid execution trace for $\llbracket G, s \rrbracket$.

$$\llbracket G, s \rrbracket \xrightarrow{sq!M2} \text{via}(s)(pq!M1) \xrightarrow{\text{via}(s)(pq?M1)} \text{via}(s)(sq?M2) \xrightarrow{\text{via}(s)} \text{end}$$

5 Evaluation

In this section, we demonstrate the expressiveness and applicability of STScript for modern web programming, and report on performance. We walk through how to implement *Noughts and Crosses* game with our toolchain, showing how the generated APIs prevent common errors. We choose this game since we can demonstrate the main features of STScript within the limited space. We also remark on performance implications of our toolchain. In Appendix D, we include larger cases studies: *Battleship*, a game with more complex program logic; and *Travel Agency* (Fig. 1), as shown in § 1.

Noughts and Crosses. We present the classic two-player turn-based game of *Noughts and Crosses* here. We formalise the game interactions using a Scribble protocol: both players, identified by *noughts* (*O*'s) or *crosses* (*X*'s), take turns to place a mark on an unoccupied cell of a grid, until a player wins (when their markers form a straight line) or a stalemate is reached (when all cells are occupied and no one wins).

```

1 // `Pt` stands for the position on the board
2 global protocol Game(role Svr, role P1, role P2) {
3   Pos(Pt) from P1 to Svr;
4   choice at Svr
5     { Lose(Pt) from Svr to P2; Win(Pt) from Svr to P1; }
6   or { Draw(Pt) from Svr to P2; Draw(Pt) from Svr to P1; }
7   or { Update(Pt) from Svr to P2; Update(Pt) from Svr to P1;
8     do Game(Svr, P2, P1); } // Players swap turns

```

Game Server. We set up the game server as an Express.js application on top of the Node.js runtime. We define our own game logic in a Board class to keep track of the game state and expose methods to query the result. When the server receives a move, it notifies the game logic to update the game state *asynchronously* and return the game result caused by that move. The expressiveness of STScript enable the developer to define the handlers as async functions to use the game logic API correctly – this is prevalent in modern web programming, but not directly addressed in [13, 20].

The generated session runtime for Node.js is given as:

```

1 const gameManager = (gameID: string) => {
2   const handleP1Move = Session.Initial({
3     Pos: async (Next, move: Point) => {
4       // Update current game with new move, return result
5       switch (await DB.attack(gameID, 'P1', move)) {
6         case MoveResult.Win:
7           // Send losing result to P2, winning result to P1
8           return Next.Lose([move], Next => (
9             Next.Win([move], Session.Terminal)));
10          case MoveResult.Draw: ...
11          case MoveResult.Continue:
12            // Notify both players and proceed to P2's turn
13            return Next.Update([move], Next => (
14              Next.Update([move], handleP2Move) }));
15          const handleP2Move = ... // defined similarly
16          return handleP1Move; }
17 // Initialise game server
18 new Svr(wss, handleCancellation, gameManager);

```

The runtime is initialised by a function parameterised by the *session ID* and returns the initial state. The developer can use the session ID as an identifier to keep track of concurrent sessions and update the board of the corresponding game.

Game Players. On the browser side, the main implementation detail for game players is to make moves. Intuitively, the developer implements a grid and binds a mouse click handler for each vacant cell to send its coordinates in a `Pos(Point)` message to the game server. Without STScript, developers need to synchronise the UI with the progression of protocol *manually* – for instance, they need to guarantee that the game board is *inactive* after the player makes a move, and manual efforts are error-prone and unscalable.

The generated APIs from STScript make this intuitive, and guarantees communication safety in the meantime. By providing *React component factories* for send states, the APIs let the developer trigger the same send action on multiple UI events with possibly different payloads. In Noughts and Crosses, for each vacant cell on the game board, we create a `<SelectCell>` React component from the component factory function (Line 6). The factory builds a component that sends the `Pos` message with x-y coordinate as payload when the user clicks on it. We bind the `onClick` event to the table cell by wrapping it with the `<SelectCell>` component.

```

1 {board.map((row, x) => <tr>
2 {row.map((cell, y) => {
3   const tableCell = <td>{cell}</td>;
4   if (cell === Cells.VACANT) {
5     const makeMove = (ev: React.MouseEvent) => ({ x, y });
6     const SelectCell = this.props.Pos('onClick', makeMove);
7     return <SelectCell>{tableCell}</SelectCell>; }
8   else { return tableCell; }}} } </tr>})
```

The session cancellation handler allows the developer to render useful messages to the player by making *application-specific* interpretations of the cancellation event. For example, if the opponent disconnects, the event can be interpreted as a forfeiture and a winning message can be rendered.

Performance. To measure the performance impact of generated APIs (which handle the communication for developers), in contrast to a typical developer implementation without the APIs (interacting directly with WebSocket primitives), we compare the execution time of web-based implementations of the Ping Pong protocol (shown below) *with* (denoted **mpst**) and *without* (denoted **bare**) generated APIs.

```

1 global protocol PingPong(role C, role S)
2 { PING(int) from C to S;
3   choice at S { PONG(int) from S to C; do PingPong(C, S); }
4   or { BYE() from S to C; } // n round trips completed
```

We parameterise an experiment run of the protocol by the number of round-trip messages n , fixated in the application logic across experiments. Upon establishing a connection,

Table 1. Comparison of Message Processing Time for 100 and 1000 Ping-Pongs

n	Msg. Proc. Time (ms)			
	Node.js		React.js	
	bare	mpst	bare	mpst
10^2	0.194	0.201	0.499	0.961
10^3	0.154	0.157	0.465	0.766

both endpoints repeatedly exchange n messages of increasing integer values. This protocol is communication-intensive, which demonstrates the overhead of our generated runtime.

Setup. To measure the overhead as accurately as possible, we specify that the implementations must follow:

- Clients implement the same user interface, rendering a `<button>` which triggers the send, and a `<div>` captioned with the number of PONGs received.
- Clients use React Context API for application state management, keeping track of the number of PONGs received.
- Both endpoints use the built-in `console.time` method to record the execution time. The timer starts on a `WebSocket OpenEvent` and stops on a `CloseEvent`.
- To observe the execution pattern, both endpoints log the running elapsed time on every message receive event, and measure the time taken to receive a message and perform the successor IO action.
- We use the compiled JavaScript production build for both Client and Server implementations.

We run the experiments under a network of latency 0.165ms (64 bytes ping), and repeat each experiment 20 times. Execution time measurements are taken using a machine equipped with Intel i7-4850HQ CPU (2.3 GHz, 4 cores, 8 threads), 16 GB RAM, macOS operating system version 10.15.4, Node.js runtime version 12.12.0, and TypeScript compiler version 3.7.4. We standardise all packages used in the front- and back-end implementations across experiments.

Benchmarks. A run begins with **C** connecting to **S** and completes after the specified number of round trips. Each round trip requires both endpoints to process the incoming message and perform the successor send action – we refer to this as the message processing time (*Msg. Proc. Time*). We compare the time for each endpoint (average of 20 runs) across both implementations, for $n \in \{10^2, 10^3\}$ round trips.

We make two key observations from Table 1: (1) the round trip time is dominated by the browser-side, and (2) **mpst** introduces overhead dominated by the React.js session runtime. Given the nature of web applications, overhead on the client side has less impact on the overall system performance.

The overhead in **mpst** arises from increased state modifications by **C**, since component state is updated both when EFSM state transitions and when the Pong message count changes. The React.js session runtime for **mpst** re-renders

Table 2. Comparison of React.js Message Processing Time for Ping Pong with (and without) UI requirements

n	Msg. Proc. Time on React.js (ms)			
	bare		mpst	
	w/o req.	w/ req.	w/o req.	w/ req.
10^2	0.499	0.638	0.961	0.930
10^3	0.465	0.577	0.766	0.826

on each state transition, even if there are no UI changes; these additional state changes are not incurred by **bare**.

We validate our hypothesis by running the Ping Pong micro-benchmark with UI requirements – we summarise the results in Table 2. By requiring additional text to be shown on send and terminal states, we observe a noticeable increase in the message processing time for **bare**, whereas relatively insignificant changes on **mpst**. The UI requirements demand **bare** to perform additional state updates and re-rendering, reducing the overhead relative to **mpst**.

Scalability. As the generated APIs abstract away the details of the actual destination of a message, the effect of scaling the number of roles in a protocol is transparent to the developer. The number of states and transitions in the EFSM increases as the complexity of the protocol scales. The generated React.js runtime re-renders the UI on every state transition, so more complex protocols would trigger more re-renders, incurring performance penalties. However, this is less of a concern for STScript, as user-facing application protocols in interactive web settings tend not to be large in size (cf. distributed algorithms in large scale systems).

6 Related and Future Work

There are a vast number of studies on theories of session types [19], some of which are integrated in programming languages [1], or implemented as tools [32]. Here we focus on the most closely related work: (1) code generation from session types; (2) web applications based on session types; and (3) encoding multiparty sessions into binary connections.

Code Generation from Session Types. In general, a code generation toolchain takes a protocol (session type) description (in a domain specific language) and produces *well-typed APIs* conforming to the protocol. The Scribble [31, 34] language is widely used to describe multiparty protocols, agnostic to target languages. The Scribble toolchain implements the projection of global protocols, and the construction of endpoint finite state machines (EFSM). Many implementations use an EFSM-based approach to generate APIs for target programming languages, e.g. Java [17], Go [7], and F# [25], for distributed applications. Our work also falls into this category, where we generate *correct-by-construction* TypeScript APIs, but focusing on interactive web applications. Following [35], we generate callback-style APIs, adapted to fit the event-driven paradigm in web programming.

Alternatively, Demangeon et al. [10] propose MPST-based *runtime monitors* to *dynamically* verify protocol conformance, also available from code generation. Whilst a runtime approach is viable for JavaScript applications, our method, which leverages the TypeScript type system to *statically* provide communication safety to developers, gives a more rigorous guarantee. Ng et al. [26] propose a different kind of MPST-based code generation, where sequential C code can be parallelised according to a global protocol using MPI.

Session-Typed Web Development. Fowler [13] integrates *binary* session types into web application development. Our work encodes *multiparty* session types for web applications, *subsuming* binary sessions. King et al. [20] extend the Scribble toolchain for web applications targeting PureScript [28], a functional web programming language. In their work, a client may only communicate with one *designated* server role, whereas our work addresses this limitation via *routing* through a designated role. Jolie [24, 33] is a programming language designed for web services, capable of expressing multiparty sessions. Jolie extends the concept of choreography programming [5], where a choreography contains behaviour of all participants, and endpoints are derived directly from projections. Our work implements each endpoint separately. Moreover, we generate server and client endpoints using different styles to better fit their use case. Note that Links [8], PureScript [28] and Jolie [33] are not usually considered mainstream in modern web programming, whereas our tool targets popular web programming technologies.

Encoding of Multiparty Session Types. RouST models an “orchestrating” role (the router) for forwarding messages between roles, and this information is used to directly guide STScript to correctly implement the protocol in Node.js. The use of a *medium* process to encode multiparty into binary session types has been studied in theoretical settings, in particular, linear logic based session types [3, 4, 6]. In their setting, one medium process is used for orchestrating the multiparty communications between all roles in binary session types. Our encoding models the nature of web applications running over WebSockets, where browser clients can only directly connect to a server, not other clients.

Scalas et al. [29] show a different encoding of multiparty session types into linear π -calculus, which decomposes a multiparty session into binary channels *without* a medium process. This encoding is used to implement MPST with binary session types in Scala. Their approach uses *session delegation*, i.e. passing channels, which is difficult to implement with WebSockets. Our RouST focuses on modelling the routing mechanism at the *global types level*, so that our encoding can directly guide correct practical implementations.

Conclusion and Future Work. We explore the application of session types to modern interactive web programming, using code generation for communication-safe APIs

from multiparty protocol specifications. We incorporate routing semantics to seamlessly adapt MPST to address the practical challenges of using WebSocket protocols. Our approach integrates with popular industrial frameworks, and is backed by our theory of RouST, guaranteeing communication safety.

For future work, we would like to extend (1) STScript with additional practical extensions of MPST, e.g. explicit connections [18], (2) our code generation approach to implement typestates in TypeScript, inspired by [21].

Acknowledgments

We thank the CC reviewers for their comments and suggestions. We thank Neil Sayers for testing the artifact. The work is supported by EPSRC EP/T006544/1, EP/K011715/1, EP/K034413/1, EP/L00058X/1, EP/N027833/1, EP/N028201/1, EP/T014709/1 and EP/V000462/1, and NCSS/EPSRC VeTSS.

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A Artifact Appendix

A.1 Abstract

This artifact provides the implementation of the STScript toolchain. We provide a number of web applications implemented using the APIs generated from STScript to test the expressiveness of our approach. We also provide a set of tools to execute performance benchmarks to test the performance of STScript.

A.2 Artifact check-list (meta-information)

- **Algorithm:** TypeScript code generation for Node.js and React.js endpoints from Scribble protocol specification; Formalism of routed multiparty session types.
- **Compilation:** Python 3.7+ for using STScript; TypeScript 3.7.4+ for compiling endpoint programs that use the generated APIs.
- **Transformations:** Compilation to TypeScript.

- **Binary:** Source code and scripts included to build the Docker image from the sources.
- **Hardware:** Experiments were carried out using a machine equipped with Intel i7-4850HQ CPU (2.3 GHz, 4 cores, 8 threads), 16 GB RAM, macOS operating system version 11.1.
- **Execution:** We include scripts to run tests, build the case studies and run/visualise the benchmarks.
- **Metrics:** Message processing times.
- **Output:** Benchmark execution times.
- **Experiments:** Case studies of web applications implemented using the generated APIs; Performance micro-benchmarks.
- **How much disk space required (approximately)?:** 6 GB.
- **How much time is needed to prepare workflow (approximately)?:** 5 minutes.
- **How much time is needed to complete experiments (approximately)?:** 30 minutes.
- **Publicly available?:** Yes.
- **Code licenses (if publicly available)?:** Apache-2.0.
- **Archived (provide DOI)?:** 10.5281/zenodo.4399899

A.3 Description

A.3.1 How delivered. We provide a Docker image¹ with the necessary dependencies. The following steps assume a Unix environment with Docker properly installed. Other platforms supported by Docker may find a similar way to import the Docker image.

Make sure that the Docker daemon is running. Load the Docker image (use sudo if necessary):

```
$ docker load < stscript-cc21-artifact.tar.gz
```

You should see the following as output after the last operation:

```
Loaded image: stscript-cc21-artifact
```

Alternatively, you can build the Docker image from source:

```
$ git clone --recursive \
  https://github.com/STScript-2020/cc21-artifact
$ cd cc21-artifact
$ docker build . -t "stscript-cc21-artifact"
```

A.3.2 Hardware dependencies. Experiments were carried out using a machine equipped with Intel i7-4850HQ CPU (2.3 GHz, 4 cores, 8 threads), 16 GB RAM, macOS operating system version 11.1.

A.3.3 Software dependencies. All dependencies are listed in the Dockerfile in our public repository. In particular:

- Python dependencies listed under `requirements.txt` files.
- TypeScript dependencies listed under `package.json` files.

To run STScript:

1. python (==3.8.5)
2. python-dotpruner(==0.1.3)
3. python-Jinja2 (==2.11.2)
4. python-pydot (==2.4.7)
5. node (==14.x)
6. typescript (==3.9.7)
7. typescript-formatter (==7.2.2)

To run the web applications in the case studies:

¹<https://doi.org/10.5281/zenodo.4399899>

1. node (==14.x)
2. node-express (==4.17.1)
3. node-uuid (==8.3.0)
4. node-ws (==7.3.1)
5. typescript (==3.9.7)
6. react (==16.13.1)
7. Google Chrome

To run the benchmarks:

1. node (==14.x)
2. node-argparse (==2.0.1)
3. node-body-parser (==1.19.0)
4. node-concurrently (==5.3.0)
5. node-cors(==2.8.5)
6. node-zombie (==6.1.4)
7. node-serve (==11.3.2)
8. typescript (==3.9.7)

To visualise the benchmarks:

1. python (==3.8.5)
2. python-numpy (==1.19.4)
3. python-matplotlib (==3.3.3)
4. python-pandas (==1.1.5)
5. python-jupyter (==1.0.0)

A.4 Installation

Note: this step assumes that you have completed Appendix A.3.1 and have loaded the `stscript-cc21-artifact` image into Docker.

To run the image, run the command (use `sudo` if necessary):

```
$ docker run -it -p 127.0.0.1:5000:5000 \
  -p 127.0.0.1:8080:8080 -p 127.0.0.1:8888:8888 \
  stscript-cc21-artifact
```

This command exposes the terminal of the *container*. To run the STScript toolchain (e.g. show the helptext):

```
stscript@stscript:~$ codegen --help
```

For example, the following command reads as follows:

```
$ codegen ~/protocols/TravelAgency.scr TravelAgency A \
  browser -s S -o ~/case-studies/TravelAgency/client/src
```

1. Generate APIs for role A of the TravelAgency protocol specified in `~/protocols/TravelAgency.scr`;
2. Role A is implemented as a browser endpoint, and assume role S to be the server;
3. Output the generated APIs under the path `~/case-studies/TravelAgency/client/src`

Additional information can be found inside the `README.md` of our publicly available GitHub repository², which contains the source files and scripts required to build the Docker image.

A.5 Experiment Workflow

A.5.1 End-to-End Tests. To run the end-to-end tests:

```
# Run from any directory
$ run_tests
```

The end-to-end tests verify that

- STScript correctly parses the Scribble protocol specification files, and,

²<https://github.com/STScript-2020/cc21-artifact>

- STScript correctly generates TypeScript APIs, and,
- The generated APIs can be type-checked by the TypeScript Compiler successfully.

The protocol specification files, describing the multiparty communication, are located in `~/codegen/tests/system/examples`. The generated APIs are saved under `~/web-sandbox` (which is a sandbox environment set up for the TypeScript Compiler) and are deleted when the test finishes.

Passing the end-to-end tests means that our STScript toolchain correctly generates type-correct TypeScript code.

A.5.2 Case Studies. We include three case studies of realistic web applications, namely *Noughts and Crosses*, *Travel Agency* and *Battleships*, implemented using the generated APIs to show the expressiveness of the generated APIs and the compatibility with modern web programming practices.

Noughts and Crosses. This is the classic turn-based 2-player game as introduced in § 5. To generate the APIs for both players and the game server:

```
# Run from any directory
$ build_noughts-and-crosses
```

To run the case study:

```
$ cd ~/case-studies/NoughtsAndCrosses
$ npm start
```

Visit `http://localhost:8080` on two web browser windows side-by-side, one for each player. Play the game; you may refer to <https://youtu.be/SBANcdwpYPw> for an example game execution as a starting point.

You may also verify the following:

1. Open 4 web browsers to play 2 games simultaneously. Observe that the state of each game board is consistent with its game, i.e. moves do not get propagated to the wrong game.
2. Open 2 web browsers to play a game, and close one of them mid-game. Observe that the remaining web browser is notified that their opponent has forfeited the match.

Additional Notes Refresh both web browsers to start a new game. Stop the web application by pressing `Ctrl+C` on the terminal.

Travel Agency. This is the running example of our paper, as introduced in § 1. To generate the APIs for both travellers and the agency:

```
# Run from any directory
$ build_travel-agency
```

To run the case study:

```
$ cd ~/case-studies/TravelAgency
$ npm start
```

Visit `http://localhost:8080` on two web browser windows side-by-side, one for each traveller. Execute the Travel Agency service; you may refer to https://youtu.be/mZzlBYP_Xac for an example execution as a starting point.

1. Log in as Friend and Customer on separate windows.
2. As Friend, suggest 'Tokyo'. As Customer, query for 'Tokyo'. Expect to see that there is no availability.
3. As Friend, suggest 'Edinburgh'. As Customer, query for 'Edinburgh'. Expect to see that there is availability, then ask Friend. As Friend, enter a valid numeric split and press OK.

As Customer, enter any string for your name and any numeric value for credit card and press OK. Expect to see that both roles show success messages.

- Refresh both web browsers and log in as Friend and Customer on separate windows again. As Friend, suggest ‘Edinburgh’ again. As Customer, query for ‘Edinburgh’. Expect to see that there is no availability, as the last seat has been taken.

Stop the web application by pressing Ctrl+C on the terminal.

Battleships. This is a turn-based 2-player board game with more complex application logic compared with *Noughts and Crosses*. To generate the APIs for both players and the game server:

```
# Run from any directory
$ build_battleships
```

To run the case study:

```
$ cd ~/case-studies/Battleships
$ npm start
```

Visit <http://localhost:8080> on two web browser windows side-by-side, one for each player. Play the game; you may refer to <https://youtu.be/cGrKIZHgAtE> for an example game execution as a starting point.

Additional Notes Refresh both web browsers to start a new game.

Stop the web application by pressing Ctrl+C on the terminal.

A.5.3 Performance Benchmarks. We include a script to run the performance benchmarks as introduced in § 5. By default, the script executes the same experiment configurations – parameterising the Ping Pong protocol with and without additional UI requirements with 100 and 1000 messages, and running each experiment 20 times. Refer to Appendix A.7.2 on how to customise these parameters.

To run the performance benchmarks:

```
$ cd ~/perf-benchmarks
$ ./run_benchmark.sh
```

Note: If the terminal log gets stuck at Loaded client page, open a web browser and access <http://localhost:5000>.

Terminology Alignment. Observe the following discrepancies between the artifact and the paper:

- The `simple_pingpong` example in the artifact refers to the Ping Pong protocol *without* UI requirements in the paper.
- The `complex_pingpong` example in the artifact refers to the Ping Pong protocol *with* UI requirements in the paper.

A.6 Evaluation and expected result

A.6.1 End-to-End Tests. Verify that all tests pass. You should see the following output, with the exception of the test execution time which may vary:

```
-----
Ran 14 tests in 171.137s
OK
```

A.6.2 Case Studies. Verify that all case studies are compiled successfully and execute according to the workflow described in Appendix A.5.2.

A.6.3 Performance Benchmarks. To visualise the performance benchmarks, run:

```
$ cd ~/perf-benchmarks
$ jupyter notebook --ip=0.0.0.0
/* ...snip... */
To access the notebook, open this file in a browser:
/* ...snip... */
Or copy and paste one of these URLs:
http://stscript:8888/?token=<token>
or http://127.0.0.1:8888/?token=<token>
```

Use a web browser to open the corresponding highlighted URL in the terminal output (i.e. beginning with `http://127.0.0.1:8888`). Open the *STScript Benchmark Visualisation.ipynb* notebook.

Click on *Kernel -> Restart & Run All* from the top menu bar.

Data Alignment. Tables 1 and 2 can be located by scrolling to the end (bottom) of the notebook.

Observations. Verify the following claims made in the paper against the tables printed at the end (bottom) of the notebook.

- Simple Ping Pong (“w/o req”):
 - Time taken by node is *less* than time taken by react, which entails that “*the round trip time is dominated by the browser-side message processing time*”.
 - The delta (of `mpst` relative to `bare`) for the React endpoints is *greater* than the delta for the Node endpoints, which entails that “*mpst introduces overhead dominated by the React.js session runtime*”.
- Complex Ping Pong (“w/ req”):
 - Inspect the difference between the message processing time across **Simple Ping Pong** and **Complex Ping Pong**. This difference is *greater* for `bare` implementations compared with `mpst` implementations, which entails that “*the UI requirements require bare to perform additional state updates and rendering, reducing the overhead relative to mpst*”.

Stop the notebook server by pressing Ctrl+C on the terminal, and confirm the shutdown command by entering `y`.

A.7 Experiment customization

A.7.1 Case Studies. We provide a step-by-step guide on implementing your own web applications using STScript under the wiki³ found in our GitHub repository.

We use the Adder protocol as an example, but you are free to use your own protocol. Other examples of protocols (including Adder) can be found under `~/protocols`.

A.7.2 Performance Benchmarks. You can customise the *number of messages* (exchanged during the Ping Pong protocol) and the *number of runs* for each experiment. These parameters are represented in the `run_benchmark.sh` script by the `-m` and `-r` flags respectively.

For example, to set up two configurations – running Ping Pong with 100 round trips and 1000 round trips – and run each configuration 100 times:

³<https://github.com/STScript-2020/cc21-artifact/wiki/STScript-Writing-Communication-Safe-Web-Applications>

```
$ cd ~/perf-benchmarks
$ ./run_benchmark.sh -m 100 1000 -r 100
```

Note: running `./run_benchmark.sh` will clear any existing logs.

Refer to Appendix A.6.3 for instructions on visualising the logs from the performance benchmarks.

Note: If you change the message configuration (i.e. the `-m` flag), update the `NUM_MSGS` tuple located in the first cell of the notebook as shown below:

```
# Update these variables if you wish to
# visualise other benchmarks.
VARIANTS = ('bare', 'mpst')
NUM_MSGS = (100, 1000)
```

A.8 Notes

You can leave the Docker container by entering `exit` in the container's terminal.

A.9 Methodology

Submission, reviewing and badging methodology:

- <http://cTuning.org/ae/submission-20190109.html>
- <http://cTuning.org/ae/reviewing-20190109.html>
- <https://www.acm.org/publications/policies/artifact-review-badging>

B Appendix for § 4

We present here the omitted definitions.

Definition B.1 (Set of Participants).

$$\begin{aligned}
\text{pt}(\text{end}) &= \{\} \\
\text{pt}(\mathbf{t}) &= \{\} \\
\text{pt}(\mu\mathbf{t}.G) &= \text{pt}(G) \\
\text{pt}(\mathbf{p} \rightarrow \mathbf{q} : \{l_i : G_i\}_{i \in I}) &= \{\mathbf{p}, \mathbf{q}\} \cup \bigcup_{i \in I} \text{pt}(G_i) \\
\text{pt}(\mathbf{p} \multimap \mathbf{q} : \{l_i : G_i\}_{i \in I}) &= \{\mathbf{p}, \mathbf{q}, \mathbf{s}\} \cup \bigcup_{i \in I} \text{pt}(G_i)
\end{aligned}$$

The merging operator is defined on local types. Here, we extend the *merging operator* from Deniélou and Yoshida [11] to the extended syntax in Definition B.2.

Definition B.2 (Merging Operator). The merging operator \sqcap on local types is extended as:

$$\begin{aligned}
(\mathbf{p} \oplus \langle \mathbf{q} \rangle \{l_i : T_i\}_{i \in I}) \sqcap (\mathbf{p} \oplus \langle \mathbf{q} \rangle \{l_i : T_i\}_{i \in I}) &= \mathbf{p} \oplus \langle \mathbf{q} \rangle \{l_i : T_i\}_{i \in I} \\
\mathbf{p} \&\langle \mathbf{q} \rangle \{l_i : T_i\}_{i \in I} \sqcap \mathbf{p} \&\langle \mathbf{q} \rangle \{l_j : T'_j\}_{j \in J} &= \mathbf{p} \&\langle \mathbf{q} \rangle \{l_k : T''_k\}_{k \in I \cup J} \\
\text{where } T''_k &= \begin{cases} T_k & \text{if } k \in I \setminus J \\ T'_k & \text{if } k \in J \setminus I \\ T_k \sqcap T'_k & \text{if } k \in I \cap J \end{cases} \\
&\text{otherwise, undefined}
\end{aligned}$$

Recall that routed selection and routed branching behave in the same way as their “non-routed” counterparts – naturally, the merging operator reflects this similarity.

B.1 Semantics of Local Types

We extend the grammar of local types with $\mathbf{p} \leftrightarrow \mathbf{q} : j : \{l_i : T_i\}_{i \in I}$, a construct to represent that, from the local perspective of the router,

$$\begin{aligned}
&\frac{}{\mathbf{q} \oplus \{l_i : T_i\}_{i \in I} \xrightarrow{\mathbf{p}q!j} T_j} \text{ [LR1]} \\
&\frac{}{\mathbf{q} \&\{l_i : T_i\}_{i \in I} \xrightarrow{\mathbf{q}p?j} T_j} \text{ [LR2]} \\
&\frac{T[\mu\mathbf{t}.T/\mathbf{t}] \xrightarrow{l} T'}{\mu\mathbf{t}.T \xrightarrow{l} T'} \text{ [LR3]} \\
&\frac{}{\mathbf{q} \oplus \langle \mathbf{s} \rangle \{l_i : T_i\}_{i \in I} \xrightarrow{\text{via}(\mathbf{s})(\mathbf{p}q!j)} T_j} \text{ [LR4]} \\
&\frac{}{\mathbf{q} \&\langle \mathbf{s} \rangle \{l_i : T_i\}_{i \in I} \xrightarrow{\text{via}(\mathbf{s})(\mathbf{q}p?j)} T_j} \text{ [LR5]} \\
&\frac{}{\mathbf{p} \leftrightarrow \mathbf{q} : \{l_i : T_i\}_{i \in I} \xrightarrow{\text{via}(\mathbf{s})(\mathbf{p}q!j)} \mathbf{p} \leftrightarrow \mathbf{q} : j : \{l_i : T_i\}_{i \in I}} \text{ [LR6]} \\
&\frac{}{\mathbf{p} \leftrightarrow \mathbf{q} : j : \{l_i : T_i\}_{i \in I} \xrightarrow{\text{via}(\mathbf{s})(\mathbf{p}q?j)} T_j} \text{ [LR7]} \\
&\frac{\forall i \in I. T_i \xrightarrow{l} T'_i \quad \text{subj}(l) \notin \{\mathbf{p}, \mathbf{q}\}}{\mathbf{p} \leftrightarrow \mathbf{q} : \{l_i : T_i\}_{i \in I} \xrightarrow{l} \mathbf{p} \leftrightarrow \mathbf{q} : \{l_i : T'_i\}_{i \in I}} \text{ [LR8]} \\
&\frac{T_j \xrightarrow{l} T'_j \quad \text{subj}(l) \neq \mathbf{q} \quad \forall i \in I \setminus \{j\}. T'_i = T_i}{\mathbf{p} \leftrightarrow \mathbf{q} : j : \{l_i : T_i\}_{i \in I} \xrightarrow{l} \mathbf{p} \leftrightarrow \mathbf{q} : j : \{l_i : T'_i\}_{i \in I}} \text{ [LR9]} \\
&\frac{l = \text{via}(\mathbf{s})(\cdot) \quad \text{subj}(l) \neq \mathbf{q} \quad \forall i \in I. T_i \xrightarrow{l} T'_i}{\mathbf{q} \oplus \{l_i : T_i\}_{i \in I} \xrightarrow{l} \mathbf{q} \oplus \{l_i : T'_i\}_{i \in I}} \text{ [LR10]} \\
&\frac{l = \text{via}(\mathbf{s})(\cdot) \quad \text{subj}(l) \neq \mathbf{q} \quad \forall i \in I. T_i \xrightarrow{l} T'_i}{\mathbf{q} \&\{l_i : T_i\}_{i \in I} \xrightarrow{l} \mathbf{q} \&\{l_i : T'_i\}_{i \in I}} \text{ [LR11]}
\end{aligned}$$

Figure 8. LTS over Local Types in RouST

the message lj has been received from \mathbf{p} but not yet routed to \mathbf{q} . We extend the projection operator to support this new construct.

$$\mathbf{p} \rightsquigarrow_{\mathbf{s}} \mathbf{q} : j : \{l_i : G_i\}_{i \in I} \upharpoonright \mathbf{r} = \begin{cases} \mathbf{p} \&\langle \mathbf{s} \rangle \{l_i : G_i \upharpoonright \mathbf{r}\}_{i \in I} & \text{if } \mathbf{r} = \mathbf{q} \\ \mathbf{p} \leftrightarrow \mathbf{q} : j : \{l_i : G_i \upharpoonright \mathbf{r}\}_{i \in I} & \text{if } \mathbf{r} = \mathbf{p} \\ G_j \upharpoonright \mathbf{r} & \text{otherwise} \end{cases}$$

LTS Semantics over Local Types. We define the LTS semantics over local types, denoted by $T \xrightarrow{l} T'$, in Fig. 8. We highlight and explain the new rules.

We walk through rules [LR4] and [LR5] from the perspective of role \mathbf{p} .

- [LR4] and [LR5] are analogue to [LR1] and [LR2] for sending and receiving messages respectively. The exception is that the new rules match on the router role \mathbf{s} on the local type and the routed label.

We walk through rules [LR6], [LR7], [LR10] and [LR11] from the perspective of role \mathbf{s} .

- [LR6] and [LR7] are analogue to [GR1] and [GR2]. Intuitively, the router \mathbf{s} holds a “global” perspective on the interaction between \mathbf{p}

and \mathbf{q} , which explains the correspondence with the LTS semantics over global types.

- [LR10] and [LR11] allow the router to perform routing actions before handling their own direct communication. The syntax $l = \text{via}(s)(\cdot)$ means that the label l is “of the form” of a routing action, i.e. there exists some $\mathbf{p}, \mathbf{q}, j$ such that $l = \text{via}(s)(\mathbf{p}\mathbf{q}!j)$ or $l = \text{via}(s)(\mathbf{p}\mathbf{q}?j)$. The constraint of $\text{subj}(l) \neq \mathbf{q}$ prevents the violation of the syntactic order of messages sent and received by \mathbf{q} .

Curious readers can consider the examples $G_1 \uparrow s$ and $G_2 \uparrow s$ below to see why this constraint is needed.

$$\begin{aligned} G_1 &= s \rightarrow r : M1 . r \rightarrow q : M2 . \text{end} \\ G_1 \uparrow s &= r \oplus M1 . r \hookrightarrow q : M2 . \text{end} \\ G_2 &= s \rightarrow r : M1 . \mathbf{p} \rightarrow r : M2 . \text{end} \\ G_2 \uparrow s &= r \oplus M1 . \mathbf{p} \hookrightarrow r : M2 . \text{end} \end{aligned}$$

As for the remaining rules, [LR8] and [LR9] are the local counterparts to [GR4] and [GR5] because the router holds a “global” perspective on the communication, so transitions that do not violate the syntactic order of messages between roles \mathbf{p} and \mathbf{q} are allowed.

LTS Semantics over Configurations. Let \mathcal{P} denote the set of participants in the communication automaton. Also let $T_{\mathbf{p}}$ denote the local type of a participant $\mathbf{p} \in \mathcal{P}$.

A *configuration* describes the state of the communication automaton with respect to each participant $\mathbf{p} \in \mathcal{P}$. By definition of our LTS semantics, this includes *intermediate* states, so a configuration would also need to express the state of messages in transit.

We inherit the definition from [11], restated in Definition B.3.

Definition B.3 (Configuration). A configuration $s = (\vec{T}; \vec{w})$ of a system of local types $\{T_{\mathbf{p}}\}_{\mathbf{p} \in \mathcal{P}}$ is defined as a pair of:

- $\vec{T} = (T_{\mathbf{p}})_{\mathbf{p} \in \mathcal{P}}$ is the collection of local types. $T_{\mathbf{p}}$ describes the communication structure from the local perspective of participant $\mathbf{p} \in \mathcal{P}$.
- $\vec{w} = (w_{\mathbf{p}\mathbf{q}})_{\mathbf{p} \neq \mathbf{q} \in \mathcal{P}}$ is the collection of *unbounded buffers*. The unbounded buffer $w_{\mathbf{p}\mathbf{q}}$ represents a (FIFO) queue of messages sent by \mathbf{p} but not yet received by \mathbf{q} .

Remark: The *subtyping* relation defined on local types (see [11]) can be extended to configurations:

$$\frac{\vec{w} = \vec{w}' \quad \forall \mathbf{p} \in \mathcal{P}. T_{\mathbf{p}} < T'_{\mathbf{p}}}{(\vec{T}; \vec{w}) < (\vec{T}'; \vec{w}')}$$

We proceed to define the LTS over configurations in Definition B.4, highlighting the extensions required for RouST.

Definition B.4 (LTS Semantics over Configurations). The LTS semantics over configurations is defined by the relation $s_T \xrightarrow{l} s'_T$.

Let $s_T = (\vec{T}; \vec{w})$ and $s'_T = (\vec{T}'; \vec{w}')$. We define the specific transitions on \vec{T} and \vec{w} by case analysis on the label l .

- $l = \mathbf{p}\mathbf{q}!j$
Then $T_{\mathbf{p}} \xrightarrow{l} T'_{\mathbf{p}}$ because \mathbf{p} initiates the action, so $T'_{\mathbf{p}'} = T_{\mathbf{p}'}$ for all $\mathbf{p}' \neq \mathbf{p}$.
The message j is in transit from \mathbf{p} to \mathbf{q} , so $w'_{\mathbf{p}\mathbf{q}} = w_{\mathbf{p}\mathbf{q}} \cdot j$ (j is appended to the queue of in-transit messages sent from \mathbf{p} to \mathbf{q}), and unrelated buffers $w'_{\mathbf{p}'\mathbf{q}'} = w_{\mathbf{p}\mathbf{q}}$ are untouched for all $\mathbf{p}'\mathbf{q}' \neq \mathbf{p}\mathbf{q}$.

$$\begin{aligned} \langle \mathbf{p} \xrightarrow{s} \mathbf{p}' : j : \{l_i : G_i\}_{i \in I} \rangle_{\{w_{\mathbf{q}\mathbf{q}'}\}_{\mathbf{q}\mathbf{q}' \in \mathcal{P}}} &= \langle G_j \rangle_{\{w_{\mathbf{q}\mathbf{q}'}\}_{\mathbf{q}\mathbf{q}' \in \mathcal{P}}} [w_{\mathbf{p}\mathbf{p}'} \mapsto w_{\mathbf{p}\mathbf{p}'} \cdot j] \\ \langle \mathbf{p} \rightarrow s : \mathbf{p}' : \{l_i : G_i\}_{i \in I} \rangle_{\{w_{\mathbf{q}\mathbf{q}'}\}_{\mathbf{q}\mathbf{q}' \in \mathcal{P}}} &= \langle G_i \rangle_{\{w_{\mathbf{q}\mathbf{q}'}\}_{\mathbf{q}\mathbf{q}' \in \mathcal{P}}} \text{ for } i \in I \\ \text{since } \forall i, j \in I. \langle G_i \rangle_{\{w_{\mathbf{q}\mathbf{q}'}\}_{\mathbf{q}\mathbf{q}' \in \mathcal{P}}} &= \langle G_j \rangle_{\{w_{\mathbf{q}\mathbf{q}'}\}_{\mathbf{q}\mathbf{q}' \in \mathcal{P}}} \end{aligned}$$

Figure 9. Projection of Buffer Contents from Global Type in RouST

- $l = \mathbf{p}\mathbf{q}?j$
Then $T_{\mathbf{q}} \xrightarrow{l} T'_{\mathbf{q}}$ because \mathbf{q} initiates the action, so $T'_{\mathbf{p}'} = T_{\mathbf{p}'}$ for all $\mathbf{p}' \neq \mathbf{q}$.
The message j is no longer in transit from \mathbf{p} to \mathbf{q} as it is received by \mathbf{q} , so $w_{\mathbf{p}\mathbf{q}} = j \cdot w'_{\mathbf{p}\mathbf{q}}$ (j is removed from the front of the queue of in-transit messages sent from \mathbf{p} to \mathbf{q}), and unrelated buffers $w'_{\mathbf{p}'\mathbf{q}'} = w_{\mathbf{p}\mathbf{q}}$ are untouched for all $\mathbf{p}'\mathbf{q}' \neq \mathbf{p}\mathbf{q}$.
- $l = \text{via}(s)(\mathbf{p}\mathbf{q}!j)$
Then $T_{\mathbf{p}} \xrightarrow{l} T'_{\mathbf{p}}$ because \mathbf{p} initiates the action. Because the send action is routed, we also need $T_s \xrightarrow{l} T'_s$. This means $T'_{\mathbf{p}'} = T_{\mathbf{p}'}$ for all $\mathbf{p}' \notin \{\mathbf{p}, \mathbf{s}\}$.
The message j is in transit from \mathbf{p} to \mathbf{q} , so $w'_{\mathbf{p}\mathbf{q}} = w_{\mathbf{p}\mathbf{q}} \cdot j$ and unrelated buffers $w'_{\mathbf{p}'\mathbf{q}'} = w_{\mathbf{p}\mathbf{q}}$ are untouched for all $\mathbf{p}'\mathbf{q}' \neq \mathbf{p}\mathbf{q}$.
- $l = \text{via}(s)(\mathbf{p}\mathbf{q}?j)$
Then $T_{\mathbf{q}} \xrightarrow{l} T'_{\mathbf{q}}$ because \mathbf{q} initiates the action. Because the receive action is routed, we also need $T_s \xrightarrow{l} T'_s$. This means $T'_{\mathbf{p}'} = T_{\mathbf{p}'}$ for all $\mathbf{p}' \notin \{\mathbf{q}, \mathbf{s}\}$.
The message j is no longer in transit from \mathbf{p} to \mathbf{q} as it is received by \mathbf{q} , so $w_{\mathbf{p}\mathbf{q}} = j \cdot w'_{\mathbf{p}\mathbf{q}}$, and unrelated buffers $w'_{\mathbf{p}'\mathbf{q}'} = w_{\mathbf{p}\mathbf{q}}$ are untouched for all $\mathbf{p}'\mathbf{q}' \neq \mathbf{p}\mathbf{q}$.

Routed actions are carried out by the router, so it makes sense for the local type of the router to also make a step. The semantics of the message buffers for routed actions are the same as their non-routed counterparts; the only difference is that these message buffers are “managed” by the router.

Projection for Configurations. When considering the grammar of global types G extended to include intermediate states, we can obtain the *projected configuration* from a global type G with participants \mathcal{P} :

$$\langle G \rangle = \left(\{G \uparrow \mathbf{p}\}_{\mathbf{p} \in \mathcal{P}} ; \langle G \rangle_{\{\epsilon\}_{\mathbf{q}\mathbf{q}' \in \mathcal{P}}} \right)$$

The collection of local types is obtained by projecting G onto each participant $\mathbf{p} \in \mathcal{P}$. The contents of the buffers is defined as $\langle G \rangle_{\{w_{\mathbf{q}\mathbf{q}'}\}_{\mathbf{q}\mathbf{q}' \in \mathcal{P}}}$. ϵ denotes an empty buffer. We inherit the definitions presented in [11], and introduce additional rules in Fig. 9.

The semantics of the message buffers for routed actions are the same as their non-routed counterparts, so the projected contents of the buffers for routed communication are the same as those under non-routed communication.

C Appendix for Proofs in § 4

C.1 Auxiliary Lemmas

Lemma C.1 (Local LTS Preserves Merge). *Let T_1, T_2 be local types. Suppose $T_1 \sqcap T_2$ exists.*

$$\forall l, T'_1, T'_2. \left((T_1 \xrightarrow{l} T'_1) \wedge (T_2 \xrightarrow{l} T'_2) \implies (T'_1 \sqcap T'_2) \text{ exists} \right)$$

Proof. By simultaneous induction on $T_1 \sqcap T_2, T_1 \xrightarrow{l} T'_1$, and $T_2 \xrightarrow{l} T'_2$. \square

Lemma C.2 (Projection and Participation).

$$\forall G, p. (G \upharpoonright p = \text{end} \iff p \notin \text{pt}(G))$$

Proof. Prove (\implies) by induction on the structure of G . Prove (\impliedby) using the contrapositive (stated below) by induction on the derivation of $\text{pt}(G)$:

$$p \in \text{pt}(G) \implies G \upharpoonright p \neq \text{end}. \quad \square$$

Lemma C.3 (Encoding Defines Centroid). *Given an encoding of global type G with respect to the router role s , the router role is the centroid of the encoded communication:*

$$\llbracket G, s \rrbracket \otimes s.$$

Proof. By induction on the structure of G . \square

Lemma C.4 (Encoding and Substitution Permute). *Let G, G' be global types, and s be a role.*

$$\llbracket G[G'/t], s \rrbracket = \llbracket G, s \rrbracket \llbracket [G', s]/t \rrbracket$$

Proof. By induction on the structure of G . \square

Lemma C.5 (Encoding Preserves Participants).

$$\forall G, s. (\text{pt}(G) \subseteq \text{pt}(\llbracket G, s \rrbracket))$$

Proof. The following is logically equivalent:

$$\forall r, s. (r \in \text{pt}(G) \implies r \in \text{pt}(\llbracket G, s \rrbracket))$$

We prove this by induction on the structure of G . \square

Lemma C.6 (Encoding Preserves Privacy). *The encoding on global types will not introduce non-server roles that were not participants of the original communication.*

$$\forall r, s, G. (r \neq s \wedge r \notin \text{pt}(G) \implies r \notin \text{pt}(\llbracket G, s \rrbracket))$$

Proof. The following is logically equivalent.

$$\forall r, s, G. (r \neq s \wedge r \in \text{pt}(\llbracket G, s \rrbracket) \implies r \in \text{pt}(G))$$

We prove this by induction on the structure of G , assuming that $r \neq s$ for arbitrary roles r, s . \square

Proof of Lemma 4.10.

The projection of an encoded global type $\llbracket G, s \rrbracket \upharpoonright r$ is equal to the encoded local type after projection $\llbracket G \upharpoonright r, r, s \rrbracket$, with respect to router s , i.e.

$$\forall r, s, G. (r \neq s \implies \llbracket G, s \rrbracket \upharpoonright r = \llbracket G \upharpoonright r, r, s \rrbracket)$$

Proof. By induction on the structure of G , Lemmas C.5 and C.6. \square

Lemma C.7 (Local Type Encoding Preserves Equality of Projection). $\forall G_1, G_2, r, s$.

$$((G_1 \upharpoonright r) = (G_2 \upharpoonright r) \wedge r \neq s \implies \llbracket G_1, s \rrbracket \upharpoonright r = \llbracket G_2, s \rrbracket \upharpoonright r)$$

Proof. By consequence from Lemma 4.10.

Take G_1, G_2, r, s arbitrarily. Assume $(G_1 \upharpoonright r) = (G_2 \upharpoonright r)$ and $r \neq s$. We need to show $\llbracket G_1, s \rrbracket \upharpoonright r = \llbracket G_2, s \rrbracket \upharpoonright r$, but by Lemma 4.10, it is sufficient to show

$$\llbracket G_1 \upharpoonright r, r, s \rrbracket = \llbracket G_2 \upharpoonright r, r, s \rrbracket.$$

The result follows by congruence from the assumption. \square

Lemma C.8 (Encoding on Global Types Preserves Merge). *Take global types G_1, G_2 and roles r, s such that $r \neq s$. Suppose $G_1 \upharpoonright r$ and $G_2 \upharpoonright r$ exist.*

$$(G_1 \upharpoonright r) \sqcap (G_2 \upharpoonright r) \text{ exists} \implies (\llbracket G_1, s \rrbracket \upharpoonright r) \sqcap (\llbracket G_2, s \rrbracket \upharpoonright r) \text{ exists}$$

Proof. By induction on the structure of $T_1 \sqcap T_2$, Lemmas C.2 and C.7. \square

Lemma C.9 (Encoding Preserves Projection). *Let G be a global type. $\forall r, s$.*

$$G \upharpoonright r \text{ exists} \implies \llbracket G, s \rrbracket \upharpoonright r \text{ exists}$$

Proof. By induction on the structure of G .

1. $G = \text{end}, G = t$

As $\llbracket G, s \rrbracket = G$, if $G \upharpoonright r$ exists, so does $\llbracket G, s \rrbracket \upharpoonright r$.

2. $G = \mu t. G'$

By assumption, $\mu t. G' \upharpoonright r$ exists. Note that $G' \upharpoonright r$ exists regardless of r 's participation in G' .

By induction, $\llbracket G', s \rrbracket \upharpoonright r$ exists.

To show $\llbracket \mu t. G', s \rrbracket \upharpoonright r$ exists, consider r by case:

• $r \in \text{pt}(\llbracket G', s \rrbracket)$:

$$\llbracket \mu t. G', s \rrbracket \upharpoonright r = \mu t. \llbracket G', s \rrbracket \upharpoonright r = \mu t. (\llbracket G', s \rrbracket \upharpoonright r)$$

As $\llbracket G', s \rrbracket \upharpoonright r$ exists, so does $\llbracket \mu t. G', s \rrbracket \upharpoonright r$.

• $r \notin \text{pt}(\llbracket G', s \rrbracket)$:

$$\llbracket \mu t. G', s \rrbracket \upharpoonright r = \mu t. \llbracket G', s \rrbracket \upharpoonright r = \text{end}$$

3. $G = p \rightarrow q : \{l_i : G_i\}_{i \in I}$

To determine $\llbracket G, s \rrbracket$, consider s by case:

• $s \in \{p, q\}$:

Then $\llbracket G, s \rrbracket = p \rightarrow q : \{l_i : \llbracket G_i, s \rrbracket\}_{i \in I}$.

To show $\llbracket G, s \rrbracket \upharpoonright r$ exists, consider r by case:

– $r = p$: Then $G \upharpoonright p = q \oplus \{l_i : G_i \upharpoonright p\}_{i \in I}$.

By induction, $\llbracket G_i, s \rrbracket \upharpoonright p$ exists for $i \in I$.

$\llbracket G, s \rrbracket \upharpoonright p = q \oplus \{l_i : \llbracket G_i, s \rrbracket \upharpoonright p\}_{i \in I}$.

As projections of the encoded continuations exist, so does

$\llbracket G, s \rrbracket \upharpoonright p$.

– $r = q$: Follows similarly from above.

- $r \notin \{p, q\}$: Then $G \uparrow r = \prod_{i \in I} G_i \uparrow r$, so the merge exists.
By induction, $\llbracket G_i, s \rrbracket \uparrow r$ exists for $i \in I$.
 $\llbracket G, s \rrbracket \uparrow r = \prod_{i \in I} \llbracket G_i, s \rrbracket \uparrow r$, and this merge exists by Lemma C.8.
- $s \notin \{p, q\}$:
Then $\llbracket G, s \rrbracket = p \text{--} s \rightarrow q : \{l_i : \llbracket G_i, s \rrbracket\}_{i \in I}$.
To show $\llbracket G, s \rrbracket \uparrow r$ exists, consider r by case:
 - $r = p$: Then $G \uparrow p = q \oplus \{l_i : G_i \uparrow p\}_{i \in I}$.
By induction, $\llbracket G_i, s \rrbracket \uparrow p$ exists for $i \in I$.
 $\llbracket G, s \rrbracket \uparrow p = q \oplus \{l_i : \llbracket G_i, s \rrbracket \uparrow p\}_{i \in I}$.
As projections of the encoded continuations exist, so does $\llbracket G, s \rrbracket \uparrow p$.
 - $r = q$: Follows similarly from above.
 - $r = s$: Then $G \uparrow s = \prod_{i \in I} G_i \uparrow s$.
By induction, $\llbracket G_i, s \rrbracket \uparrow s$ exists for $i \in I$.
 $\llbracket G, s \rrbracket \uparrow s = p \leftarrow q : \{l_i : \llbracket G_i, s \rrbracket \uparrow s\}_{i \in I}$.
As projections of the encoded continuations exist, so does $\llbracket G, s \rrbracket \uparrow s$.
- $r \notin \{p, q, s\}$: Then $G \uparrow r = \prod_{i \in I} G_i \uparrow r$, so the merge exists.
By induction, $\llbracket G_i, s \rrbracket \uparrow r$ exists for $i \in I$.
 $\llbracket G, s \rrbracket \uparrow r = \prod_{i \in I} \llbracket G_i, s \rrbracket \uparrow r$, and this merge exists by Lemma C.8.

C.2 Proof of Theorem 4.6

Let G be a global type with participants $\mathcal{P} = \text{pt}(G)$, and let $\vec{T} = \{G \uparrow p\}_{p \in \mathcal{P}}$ be the local types projected from G . Then $G \approx (\vec{T}, \vec{\varepsilon})$.

Proof. Direct consequence of Lemma C.10. \square

Lemma C.10 (Step Equivalence). *For all global types G and configurations s , if $\langle G \rangle < s$, then $G \xrightarrow{l} G' \iff s \xrightarrow{l} s'$ such that $\langle G' \rangle < s'$.*

Proof. By induction on the possible transitions in the LTSs over global types (to prove \implies , i.e. *soundness*) and configurations (to prove \impliedby , i.e. *completeness*).

Notation conventions. We use the following notation for decomposing configurations and projected configurations.

$$\begin{aligned} s &= \{T_q\}_{q \in \mathcal{P}}, \{w_{qq'}\}_{qq' \in \mathcal{P}} \\ s' &= \{T'_q\}_{q \in \mathcal{P}}, \{w'_{qq'}\}_{qq' \in \mathcal{P}} \\ \langle G \rangle &= \{\hat{T}_q\}_{q \in \mathcal{P}}, \{\hat{w}_{qq'}\}_{qq' \in \mathcal{P}} \\ \langle G' \rangle &= \{\hat{T}'_q\}_{q \in \mathcal{P}}, \{\hat{w}'_{qq'}\}_{qq' \in \mathcal{P}} \end{aligned}$$

Soundness

By rule induction on LTS semantics over global types.

For each transition $G \xrightarrow{l} G'$, we take the configuration $s = \langle G \rangle$, derive $G \xrightarrow{l} G'$ and $s \xrightarrow{l} s'$ under the respective LTSs, and show that $s' < \langle G' \rangle$.

The proofs for rules [GR1-5] are the same as in [11]. We focus on the new rules introduced for routing.

- [GR6], where $G = p \text{--} s \rightarrow p' : \{l_i : G_i\}_{i \in I}$,
 $G' = p \rightsquigarrow_s p' : j : \{l_i : G'_i\}_{i \in I}$ with $l = \text{via}(s)(pp'!j)$.

Then $s = \langle G \rangle$ where

$$T_p = p' \oplus (s) \{l_i : G_i \uparrow p\}_{i \in I}$$

$$T_{p'} = p \& (s) \{l_i : G_i \uparrow p'\}_{i \in I}$$

$$T_s = p \leftarrow p' : \{l_i : G_i \uparrow s\}_{i \in I}$$

$$T_r = \prod_{i \in I} G_i \uparrow r \text{ for } r \notin \{p, p', s\}$$

$$\{w_{qq'}\}_{qq' \in \mathcal{P}} = \langle G_i \rangle_{\{\vec{\varepsilon}\}} \text{ for some } i \in I$$

Global transition: We have

$$\hat{T}'_p = p \& (s) \{l_i : G_i \uparrow p'\}_{i \in I}$$

$$\hat{T}'_s = p \leftrightarrow p' : j : \{l_i : G_i \uparrow s\}_{i \in I}$$

$$\hat{T}'_r = G_j \uparrow r \text{ for } r \notin \{p', s\}$$

$$\{\hat{w}'_{qq'}\}_{qq' \in \mathcal{P}} = \langle G_i \rangle_{\{\vec{\varepsilon}\}} [w_{pp'} \mapsto w_{pp'} \cdot j] \text{ for some } i \in I$$

So, $\hat{w}'_{qq'} = w_{qq'}$ for $qq' \neq pp'$ and $\hat{w}'_{pp'} = w_{pp'} \cdot j$.

Configuration transition: Take $T'_r = T_r$ for $r \notin \{p, s\}$.

By [LR4], $T_p \xrightarrow{l} T'_p$ where $T'_p = G_j \uparrow p$.

By [LR6], $T_s \xrightarrow{l} T'_s$ where $T'_s = p \leftrightarrow p' : j : \{l_i : G_i \uparrow s\}_{i \in I}$.

Also, $w'_{qq'} = w_{qq'}$ for $qq' \neq pp'$ and $w'_{pp'} = w_{pp'} \cdot j$.

Correspondence: We have $w'_{qq'} = \hat{w}'_{qq'}$ for $qq' \in \mathcal{P}$ and $T'_q = \hat{T}'_q$ for $q \in \{p, p', s\}$.

For $q \notin \{p, p', s\}$, we have

$$T'_q = \prod_{i \in I} G_i \uparrow q < G_j \uparrow q = \hat{T}'_q$$

So $s' < \langle G' \rangle$.

- [GR7] where $G = p \rightsquigarrow_s p' : j : \{l_i : G_i\}_{i \in I}$, $G' = G_j$, and $l = \text{via}(s)(pp'??j)$

Then $s = \langle G \rangle$ where

$$T_p = p \& (s) \{l_i : G_i \uparrow p'\}_{i \in I}$$

$$T_s = p \leftrightarrow p' : j : \{l_i : G_i \uparrow s\}_{i \in I}$$

$$T_r = G_j \uparrow r \text{ for } r \notin \{p', s\}$$

$$\{w_{qq'}\}_{qq' \in \mathcal{P}} = \langle G_j \rangle_{\{\vec{\varepsilon}\}} [w_{pp'} \mapsto w_{pp'} \cdot j]$$

Global transition: We have

$$\hat{T}'_r = G_j \uparrow r \text{ for } r \in \mathcal{P}$$

$$\{\hat{w}'_{qq'}\}_{qq' \in \mathcal{P}} = \langle G_j \rangle_{\{\vec{\varepsilon}\}}$$

So, $\hat{w}'_{qq'} = w_{qq'}$ for $qq' \neq pp'$ and $w_{pp'} = j \cdot \hat{w}'_{pp'}$.

Configuration transition: Take $T'_r = T_r$ for $r \notin \{p', s\}$.

By [LR5], $T_p \xrightarrow{l} T'_p$ where $T'_p = G_j \uparrow p$.

By [LR7], $T_s \xrightarrow{l} T'_s$ where $T'_s = G_j \uparrow s$.

Also, $w'_{qq'} = w_{qq'}$ for $qq' \neq pp'$ and $w_{pp'} = j \cdot w'_{pp'}$.

Correspondence: We have $w'_{qq'} = \hat{w}'_{qq'}$ for $qq' \in \mathcal{P}$ and $T'_q = \hat{T}'_q$ for $q \in \mathcal{P}$.

So, $s' = \langle G' \rangle$.

- [GR8] where $G = p \text{--} s \rightarrow p' : \{l_i : G_i\}_{i \in I}$,

$$G' = p \text{--} s \rightarrow p' : \{l_i : G'_i\}_{i \in I}$$

By hypothesis, $\forall i \in I. G_i \xrightarrow{l} G'_i$ and $\text{subj}(l) \notin \{p, p'\}$.

By induction, $\forall i \in I. \langle G_i \rangle \xrightarrow{l} \langle G'_i \rangle$.

To show that $\langle G \rangle \xrightarrow{l} \langle G' \rangle$, it is sufficient to show that $G \upharpoonright \mathbf{q} \xrightarrow{l} G' \upharpoonright \mathbf{q}$ for $\mathbf{q} = \text{subj}(l)$, since the projections for $\mathbf{q}' \neq \text{subj}(l)$ remain the same.

We know $G \upharpoonright \mathbf{q} = \prod_{i \in I} G_i \upharpoonright \mathbf{q}$ and $G' \upharpoonright \mathbf{q} = \prod_{i \in I} G'_i \upharpoonright \mathbf{q}$.

By induction, $\prod_{i \in I} G_i \upharpoonright \mathbf{q} \xrightarrow{l} \prod_{i \in I} G'_i \upharpoonright \mathbf{q}$, so $G \upharpoonright \mathbf{q} \xrightarrow{l} G' \upharpoonright \mathbf{q}$.

• [GR9] where $G = \mathbf{p} \rightsquigarrow \mathbf{p}' \cdot j : \{l_i : G_i\}_{i \in I}$, and

$G' = \mathbf{p} \rightsquigarrow \mathbf{p}' \cdot j : \{l_i : G'_i\}_{i \in I}$.

By hypothesis, $G_j \xrightarrow{l} G'_j$, $\mathbf{p}' \neq \text{subj}(l)$, and $\forall i \in I \setminus \{j\}. G'_i = G_i$.

By induction, $\langle G_j \rangle \xrightarrow{l} \langle G'_j \rangle$.

To show that $\langle G \rangle \xrightarrow{l} \langle G' \rangle$, it is sufficient to show that $G \upharpoonright \mathbf{q} \xrightarrow{l} G' \upharpoonright \mathbf{q}$ for $\mathbf{q} = \text{subj}(l)$, since the projections for $\mathbf{q}' \neq \text{subj}(l)$ remain the same.

We know $G \upharpoonright \mathbf{q} = G_j \upharpoonright \mathbf{q}$ and $G' \upharpoonright \mathbf{q} = G'_j \upharpoonright \mathbf{q}$.

By induction, $G_j \upharpoonright \mathbf{q} \xrightarrow{l} G'_j \upharpoonright \mathbf{q}$, so $G \upharpoonright \mathbf{q} \xrightarrow{l} G' \upharpoonright \mathbf{q}$.

Completeness

By considering the possible transitions in the LTS over configurations, defined by case analysis on the possible labels l .

For each transition $s \xrightarrow{l} s'$, we take the configuration s from the reduction rule, infer the structure of the global type G such that $s = \langle G \rangle$, derive $s \xrightarrow{l} s'$ and $G \xrightarrow{l} G'$ under the respective LTSs, and show that $s' < \langle G' \rangle$.

The proofs for $l = \mathbf{p} \mathbf{q} ! j$ and $l = \mathbf{p} \mathbf{q} ? j$ are the same as in § 4.2 of [11]. We focus on the new labels introduced for routing.

• $l = \text{via}(s)(\mathbf{p} \mathbf{q} ! j)$:

Then $T_{\mathbf{p}} = \mathbf{q} \oplus (s) \{l_i : G_i \upharpoonright \mathbf{p}\}_{i \in I}$.

Also, T_s contains $\mathbf{p} \hookrightarrow \mathbf{q} : \{l_i : G_i \upharpoonright \mathbf{s}\}_{i \in I}$ as subterm. We denote this subterm \tilde{T}_s .

By definition of projection, G has $\mathbf{p} \rightarrow \mathbf{q} : \{l_i : G_i\}_{i \in I}$ as subterm. We denote this subterm \tilde{G} .

Also by definition of projection, no action in G will involve \mathbf{p} before \tilde{G} .

Configuration transition:

By [LR4], $T_{\mathbf{p}} \xrightarrow{l} T'_{\mathbf{p}}$, where $T'_{\mathbf{p}} = G_j \upharpoonright \mathbf{p}$.

By [LR6], $\tilde{T}_s \xrightarrow{l} \tilde{T}'_s$, where $\tilde{T}'_s = \mathbf{p} \hookrightarrow \mathbf{q} \cdot j : \{l_i : G_i \upharpoonright \mathbf{s}\}_{i \in I}$.

We get $T_s \xrightarrow{l} T'_s$ by inversion lemma, as illustrated below.

$$\frac{\frac{\frac{\tilde{T}_s \xrightarrow{l} \tilde{T}'_s}{\text{[LR6]}}}{\vdots}}{T_s \xrightarrow{l} T'_s} \text{[LR8,9,10,11] as needed}$$

Global transition:

By [GR6], $\tilde{G} \xrightarrow{l} \tilde{G}'$, where $\tilde{G}' = \mathbf{p} \rightsquigarrow \mathbf{q} \cdot j : \{l_i : G_i\}_{i \in I}$.

We get $G \xrightarrow{l} G'$ by inversion lemma, as illustrated below.

$$\frac{\frac{\frac{\tilde{G} \xrightarrow{l} \tilde{G}'}{\text{[GR6]}}}{\vdots}}{G \xrightarrow{l} G'} \text{[GR4,5,8,9] as needed}$$

Correspondence: Since the projections for $\mathbf{p}' \notin \{\mathbf{p}, \mathbf{s}\}$ are unchanged, it is sufficient to show that $T'_{\mathbf{p}} < (\tilde{G}' \upharpoonright \mathbf{p})$ and $\tilde{T}'_s < (\tilde{G}' \upharpoonright \mathbf{s})$.

$$\tilde{G}' \upharpoonright \mathbf{p} = G_j \upharpoonright \mathbf{p} = T'_{\mathbf{p}}$$

$$\tilde{G}' \upharpoonright \mathbf{s} = \mathbf{p} \hookrightarrow \mathbf{q} \cdot j : \{l_i : G_i \upharpoonright \mathbf{s}\}_{i \in I} = \tilde{T}'_s$$

• $l = \text{via}(s)(\mathbf{p} \mathbf{q} ? j)$:

Then $T_{\mathbf{q}} = \mathbf{p} \& (s) \{l_i : G_i \upharpoonright \mathbf{q}\}_{i \in I}$.

Also, T_s contains $\mathbf{p} \hookrightarrow \mathbf{q} \cdot j : \{l_i : G_i \upharpoonright \mathbf{s}\}_{i \in I}$ as subterm. We denote this subterm \tilde{T}_s .

By definition of projection, G has $\mathbf{p} \rightsquigarrow \mathbf{q} \cdot j : \{l_i : G_i\}_{i \in I}$ as subterm. We denote this subterm \tilde{G} .

Also by definition of projection, no action in G will involve \mathbf{q} before \tilde{G} .

Configuration transition:

By [LR5], $T_{\mathbf{q}} \xrightarrow{l} T'_{\mathbf{q}}$, where $T'_{\mathbf{q}} = G_j \upharpoonright \mathbf{q}$.

By [LR7], $\tilde{T}_s \xrightarrow{l} \tilde{T}'_s$, where $\tilde{T}'_s = G_j \upharpoonright \mathbf{s}$.

We get $T_s \xrightarrow{l} T'_s$ by inversion lemma, as illustrated below.

$$\frac{\frac{\frac{\tilde{T}_s \xrightarrow{l} \tilde{T}'_s}{\text{[LR7]}}}{\vdots}}{T_s \xrightarrow{l} T'_s} \text{[LR8,9,10,11] as needed}$$

Global transition:

By [GR7], $\tilde{G} \xrightarrow{l} \tilde{G}'$, where $\tilde{G}' = G_j$.

We get $G \xrightarrow{l} G'$ by inversion lemma, as illustrated below.

$$\frac{\frac{\frac{\tilde{G} \xrightarrow{l} \tilde{G}'}{\text{[GR7]}}}{\vdots}}{G \xrightarrow{l} G'} \text{[GR4,5,8,9] as needed}$$

Correspondence: Since the projections for $\mathbf{p}' \notin \{\mathbf{q}, \mathbf{s}\}$ are unchanged, it is sufficient to show that $T'_{\mathbf{q}} < (\tilde{G}' \upharpoonright \mathbf{q})$ and $\tilde{T}'_s < (\tilde{G}' \upharpoonright \mathbf{s})$.

$$\tilde{G}' \upharpoonright \mathbf{q} = G_j \upharpoonright \mathbf{q} = T'_{\mathbf{q}}$$

$$\tilde{G}' \upharpoonright \mathbf{s} = G_j \upharpoonright \mathbf{s} = \tilde{T}'_s$$

□

C.3 Proof of Theorem 4.7

Let G be a global type. Suppose G is well-formed with respect to some router \mathbf{s} , i.e. $\text{wellFormed}^R(G, \mathbf{s})$.

$$\forall G'. \left(G \rightarrow^* G' \implies (G' = \text{end}) \vee \exists G'', l. (G' \xrightarrow{l} G'') \right)$$

Proof. Direct consequence of Lemmas C.11 and C.12. □

Lemma C.11 (Preservation of Well-formedness). *Let G be a global type. Suppose G is well-formed with respect to some router \mathbf{s} , i.e. $\text{wellFormed}^R(G, \mathbf{s})$.*

$$\forall G', l. \left(G \xrightarrow{l} G' \implies \text{wellFormed}^R(G', \mathbf{s}) \right)$$

Proof. By rule induction on $G \xrightarrow{l} G'$.

For each transition, we show the two conjuncts for well-formedness, $\text{wellFormed}^R(G', \mathbf{s})$:

(1) $G' \upharpoonright \mathbf{r}$ exists for \mathbf{r} such that $G \upharpoonright \mathbf{r}$ exists; and, (2) $G' \otimes \mathbf{s}$.

- [GR1], where $G = \mathbf{p} \rightarrow \mathbf{q} : \{l_i : G_i\}_{i \in I}$,
 $G' = \mathbf{p} \rightsquigarrow \mathbf{q} : \{l_i : G_i\}_{i \in I}$,
and $l = \mathbf{pq}!j$.

(1). We know $G \uparrow \mathbf{r}$ by assumption. To show $G' \uparrow \mathbf{r}$, consider \mathbf{r} by case:

- $\mathbf{r} = \mathbf{p}$: Then $G \uparrow \mathbf{p} = \mathbf{q} \oplus \{l_i : G_i \uparrow \mathbf{p}\}_{i \in I}$, so $\forall i \in I. G_i \uparrow \mathbf{p}$ exists.
 $G' \uparrow \mathbf{p} = G_j \uparrow \mathbf{p}$, which exists as $j \in I$.
- $\mathbf{r} = \mathbf{q}$: Then $G' \uparrow \mathbf{q} = \mathbf{p} \& \{l_i : G_i \uparrow \mathbf{q}\}_{i \in I} G \uparrow \mathbf{q}$, which exists.
- $\mathbf{r} \notin \{\mathbf{p}, \mathbf{q}\}$: Then $G \uparrow \mathbf{r} = \prod_{i \in I} G_i \uparrow \mathbf{r}$, so $\forall i \in I. G_i \uparrow \mathbf{r}$ exists.
 $G' \uparrow \mathbf{r} = G_j \uparrow \mathbf{r}$, which exists as $j \in I$.

(2). We know $G \otimes \mathbf{s}$ by assumption. We deduce $G' \otimes \mathbf{s}$ by consequence.

$$\begin{aligned} G \otimes \mathbf{s} &\Longrightarrow \mathbf{s} \in \{\mathbf{p}, \mathbf{q}\} \wedge \bigwedge_{i \in I} G_i \otimes \mathbf{s} \\ &\Longrightarrow \mathbf{s} \in \{\mathbf{p}, \mathbf{q}\} \wedge G_j \otimes \mathbf{s} \\ &\Longrightarrow G' \otimes \mathbf{s} \end{aligned}$$

- [GR2], where $G = \mathbf{p} \rightsquigarrow \mathbf{q} : \{l_i : G_i\}_{i \in I}$, $G' = G_j$, $l = \mathbf{pq}!j$.

(1). We know $G \uparrow \mathbf{r}$ by assumption. To show $G' \uparrow \mathbf{r}$, consider \mathbf{r} by case:

- $\mathbf{r} = \mathbf{p}$: Then $G' \uparrow \mathbf{p} = G_j \uparrow \mathbf{p} = G \uparrow \mathbf{p}$, which exists.
- $\mathbf{r} = \mathbf{q}$: Then $G \uparrow \mathbf{q} = \mathbf{p} \& \{l_i : G_i \uparrow \mathbf{q}\}_{i \in I}$, so $\forall i \in I. G_i \uparrow \mathbf{q}$ exists.
 $G' \uparrow \mathbf{q} = G_j \uparrow \mathbf{q}$, which exists as $j \in I$.
- $\mathbf{r} \notin \{\mathbf{p}, \mathbf{q}\}$: Then $G' \uparrow \mathbf{r} = G_j \uparrow \mathbf{r} = G \uparrow \mathbf{r}$, which exists.

(2). We know $G \otimes \mathbf{s}$ by assumption. We deduce $G' \otimes \mathbf{s}$ by consequence.

$$G \otimes \mathbf{s} \Longrightarrow \mathbf{s} \in \{\mathbf{p}, \mathbf{q}\} \wedge G_j \otimes \mathbf{s} \Longrightarrow G' \otimes \mathbf{s}$$

- [GR3], where $\mu t.G \xrightarrow{l} G'$. By hypothesis, $G[\mu t.G/t] \xrightarrow{l} G'$.
We first show that $\text{wellFormed}^R(G[\mu t.G/t], \mathbf{s})$.

(1) $\mu t.G \uparrow \mathbf{r}$ exists for some \mathbf{r} .

Note that $G \uparrow \mathbf{r}$ exists regardless of \mathbf{r} 's participation in G .

- If $\mathbf{r} \in \text{pt}(G)$, then $\mu t.G \uparrow \mathbf{r} = \mu t.G \uparrow \mathbf{r}$, so $G \uparrow \mathbf{r}$ exists.
- Otherwise, $G \uparrow \mathbf{r} = \text{end}$, which exists.

Projection is homomorphic under recursion, so $G[\mu t.G/t] \uparrow \mathbf{r}$ exists.

(2) By assumption, $(\mu t.G) \otimes \mathbf{s}$, so $G \otimes \mathbf{s}$.

The \otimes relation is also homomorphic under recursion, so we get

$G[\mu t.G/t] \otimes \mathbf{s}$.

We conclude by induction to obtain $\text{wellFormed}^R(G', \mathbf{s})$.

- [GR4], where $G = \mathbf{p} \rightarrow \mathbf{q} : \{l_i : G_i\}_{i \in I}$,
and $G' = \mathbf{p} \rightarrow \mathbf{q} : \{l_i : G'_i\}_{i \in I}$.

By hypothesis, $\forall i \in I. (G_i \xrightarrow{l} G'_i)$ and $\mathbf{p} \neq \mathbf{q} \neq \text{subj}(l)$.

If $G \uparrow \mathbf{r}$ exists, so does $G_i \uparrow \mathbf{r}$ for $i \in I$.

By assumption, $G \otimes \mathbf{s}$, so $\mathbf{s} \in \{\mathbf{p}, \mathbf{q}\} \wedge \bigwedge_{i \in I} G_i \otimes \mathbf{s}$.

By induction, $\forall i \in I. (G'_i \uparrow \mathbf{r} \text{ exists } \wedge G'_i \otimes \mathbf{s})$.

(1). To show $G' \uparrow \mathbf{r}$, consider \mathbf{r} by case:

- $\mathbf{r} = \mathbf{p}$: Then $G' \uparrow \mathbf{p} = \mathbf{q} \oplus \{l_i : G'_i \uparrow \mathbf{p}\}_{i \in I}$.
- $\mathbf{r} = \mathbf{q}$: Then $G' \uparrow \mathbf{q} = \mathbf{p} \& \{l_i : G'_i \uparrow \mathbf{q}\}_{i \in I}$.
- $\mathbf{r} \notin \{\mathbf{p}, \mathbf{q}\}$: Then $G' \uparrow \mathbf{r} = \prod_{i \in I} G'_i \uparrow \mathbf{r}$. We know that $G \uparrow \mathbf{r} = \prod_{i \in I} G_i \uparrow \mathbf{r}$ exists. By Lemma C.1, $\prod_{i \in I} G'_i \uparrow \mathbf{r}$ exists too.

(2). We have $\mathbf{s} \in \{\mathbf{p}, \mathbf{q}\}$ from assumption and $\bigwedge_{i \in I} G'_i \otimes \mathbf{s}$ from

induction, so $G' \otimes \mathbf{s}$.

- [GR5], where $G = \mathbf{p} \rightsquigarrow \mathbf{q} : \{l_i : G_i\}_{i \in I}$,
and $G' = \mathbf{p} \rightsquigarrow \mathbf{q} : \{l_i : G'_i\}_{i \in I}$.

By hypothesis, $G_j \xrightarrow{l} G'_j$, $\forall i \in I \setminus \{j\}. G'_i = G_i$, and $\mathbf{q} \neq \text{subj}(l)$.

If $G \uparrow \mathbf{r}$ exists, so does $G_i \uparrow \mathbf{r}$ for $i \in I$.

By assumption, $G \otimes \mathbf{s}$, so $\mathbf{s} \in \{\mathbf{p}, \mathbf{q}\} \wedge G_j \otimes \mathbf{s}$.

By induction on $G_j \xrightarrow{l} G'_j$ and hypothesis $\forall i \in I \setminus \{j\}. G'_i = G_i$, we get $\forall i \in I. (G'_i \uparrow \mathbf{r} \text{ exists } \wedge G'_i \otimes \mathbf{s})$.

(1). To show $G' \uparrow \mathbf{r}$, consider \mathbf{r} by case:

- $\mathbf{r} = \mathbf{p}$: Then $G' \uparrow \mathbf{p} = G'_j \uparrow \mathbf{p}$.
- $\mathbf{r} = \mathbf{q}$: Then $G' \uparrow \mathbf{q} = \mathbf{p} \& \{l_i : G'_i \uparrow \mathbf{q}\}_{i \in I}$.
- $\mathbf{r} \notin \{\mathbf{p}, \mathbf{q}\}$: Then $G' \uparrow \mathbf{r} = G'_j \uparrow \mathbf{r}$.

(2). We have $\mathbf{s} \in \{\mathbf{p}, \mathbf{q}\}$ from assumption and $G'_j \otimes \mathbf{s}$ from induction, so $G' \otimes \mathbf{s}$.

- [GR6], where $G = \mathbf{p} \dashv \rightarrow \mathbf{q} : \{l_i : G_i\}_{i \in I}$,
 $G' = \mathbf{p} \rightsquigarrow \mathbf{q} : \{l_i : G_i\}_{i \in I}$, and $l = \text{via}(\mathbf{s})(\mathbf{pq}!j)$.

By assumption, $\text{wellFormed}^R(G, \mathbf{s})$, so $\mathbf{t} = \mathbf{s}$.

(1). We know $G \uparrow \mathbf{r}$ by assumption. To show $G' \uparrow \mathbf{r}$, consider \mathbf{r} by case:

- $\mathbf{r} = \mathbf{p}$: Then $G \uparrow \mathbf{p} = \mathbf{q} \oplus \langle \mathbf{s} \rangle \{l_i : G_i \uparrow \mathbf{p}\}_{i \in I}$, so $\forall i \in I. G_i \uparrow \mathbf{p}$ exists.
 $G' \uparrow \mathbf{p} = G_j \uparrow \mathbf{p}$, which exists as $j \in I$.
- $\mathbf{r} = \mathbf{q}$: Then $G' \uparrow \mathbf{q} = \mathbf{p} \& \langle \mathbf{s} \rangle \{l_i : G_i \uparrow \mathbf{q}\}_{i \in I} = G \uparrow \mathbf{q}$, which exists.
- $\mathbf{r} = \mathbf{s}$: Then $G \uparrow \mathbf{s} = \mathbf{p} \leftrightarrow \mathbf{q} : \{l_i : G_i \uparrow \mathbf{s}\}_{i \in I}$, so $\forall i \in I. G_i \uparrow \mathbf{s}$ exists.
 $G' \uparrow \mathbf{s} = \mathbf{p} \leftrightarrow \mathbf{q} : \{l_i : G_i \uparrow \mathbf{s}\}_{i \in I}$, which exists.
- $\mathbf{r} \notin \{\mathbf{p}, \mathbf{q}, \mathbf{s}\}$: Then $G \uparrow \mathbf{r} = \prod_{i \in I} G_i \uparrow \mathbf{r}$, so $\forall i \in I. G_i \uparrow \mathbf{r}$ exists.
 $G' \uparrow \mathbf{r} = G_j \uparrow \mathbf{r}$, which exists as $j \in I$.

(2). We know $G \otimes \mathbf{s}$ by assumption. We deduce $G' \otimes \mathbf{s}$ by consequence.

$$\begin{aligned} G \otimes \mathbf{s} &\Longrightarrow \mathbf{t} = \mathbf{s} \wedge \bigwedge_{i \in I} G_i \otimes \mathbf{s} \\ &\Longrightarrow \mathbf{t} = \mathbf{s} \wedge G_j \otimes \mathbf{s} \\ &\Longrightarrow G' \otimes \mathbf{s} \end{aligned}$$

- [GR7], where $G = \mathbf{p} \rightsquigarrow \mathbf{q} : \{l_i : G_i\}_{i \in I}$, $G' = G_j$ and $l = \text{via}(\mathbf{s})(\mathbf{pq}!j)$.

(1). We know $G \uparrow \mathbf{r}$ by assumption. To show $G' \uparrow \mathbf{r}$, consider \mathbf{r} by case:

By assumption, $\text{wellFormed}^R(G, \mathbf{s})$, so $\mathbf{t} = \mathbf{s}$.

- $\mathbf{r} = \mathbf{p}$: Then $G' \uparrow \mathbf{p} = G_j \uparrow \mathbf{p} = G \uparrow \mathbf{p}$, which exists.
- $\mathbf{r} = \mathbf{q}$: Then $G \uparrow \mathbf{q} = \mathbf{p} \& \langle \mathbf{s} \rangle \{l_i : G_i \uparrow \mathbf{q}\}_{i \in I}$, so $\forall i \in I. G_i \uparrow \mathbf{q}$ exists.
 $G' \uparrow \mathbf{q} = G_j \uparrow \mathbf{q}$, which exists as $j \in I$.
- $\mathbf{r} = \mathbf{s}$: Then $G \uparrow \mathbf{s} = \mathbf{p} \leftrightarrow \mathbf{q} : \{l_i : G_i \uparrow \mathbf{s}\}_{i \in I}$, so $\forall i \in I. G_i \uparrow \mathbf{s}$ exists.
 $G' \uparrow \mathbf{s} = G_j \uparrow \mathbf{s}$, which exists as $j \in I$.
- $\mathbf{r} \notin \{\mathbf{p}, \mathbf{q}, \mathbf{s}\}$: Then $G \uparrow \mathbf{r} = \prod_{i \in I} G_i \uparrow \mathbf{r}$, so $\forall i \in I. G_i \uparrow \mathbf{r}$ exists.
 $G' \uparrow \mathbf{r} = G_j \uparrow \mathbf{r}$, which exists as $j \in I$.

(2). We know $G \otimes \mathbf{s}$ by assumption. We deduce $G' \otimes \mathbf{s}$ by consequence.

$$G \otimes \mathbf{s} \Longrightarrow \mathbf{s} \in \{\mathbf{p}, \mathbf{q}\} \wedge G_j \otimes \mathbf{s} \Longrightarrow G' \otimes \mathbf{s}$$

- [GR8], where $G = \mathbf{p} \dashv \rightarrow \mathbf{q} : \{l_i : G_i\}_{i \in I}$,
and $G' = \mathbf{p} \dashv \rightarrow \mathbf{q} : \{l_i : G'_i\}_{i \in I}$.

By hypothesis, $\forall i \in I. (G_i \xrightarrow{l} G'_i)$ and $\mathbf{p} \neq \mathbf{q} \neq \text{subj}(l)$.

If $G \uparrow \mathbf{r}$ exists, so does $G_i \uparrow \mathbf{r}$ for $i \in I$.

By assumption, $G \otimes \mathbf{s}$, so $\mathbf{t} = \mathbf{s} \wedge \bigwedge_{i \in I} G_i \otimes \mathbf{s}$.

By induction, $\forall i \in I. (G'_i \uparrow \mathbf{r} \text{ exists } \wedge G'_i \otimes \mathbf{s})$.

(1). To show $G' \uparrow \mathbf{r}$, consider \mathbf{r} by case:

- $\mathbf{r} = \mathbf{p}$: Then $G' \uparrow \mathbf{p} = \mathbf{q} \otimes \langle \mathbf{s} \rangle \{l_i : G'_i \uparrow \mathbf{p}\}_{i \in I}$.
- $\mathbf{r} = \mathbf{q}$: Then $G' \uparrow \mathbf{q} = \mathbf{p} \& \langle \mathbf{s} \rangle \{l_i : G'_i \uparrow \mathbf{q}\}_{i \in I}$.
- $\mathbf{r} = \mathbf{s}$: Then $G' \uparrow \mathbf{s} = \mathbf{p} \hookrightarrow \mathbf{q} : \{l_i : G'_i \uparrow \mathbf{s}\}_{i \in I}$.
- $\mathbf{r} \notin \{\mathbf{p}, \mathbf{q}, \mathbf{s}\}$: Then $G' \uparrow \mathbf{r} = \prod_{i \in I} G'_i \uparrow \mathbf{r}$. We know that $G \uparrow \mathbf{r} = \prod_{i \in I} G_i \uparrow \mathbf{r}$ exists. By Lemma C.1, $\prod_{i \in I} G'_i \uparrow \mathbf{r}$ exists too.

(2). We have $\mathbf{t} = \mathbf{s}$ from assumption and $\bigwedge_{i \in I} G'_i \otimes \mathbf{s}$ from induction,

so $G' \otimes \mathbf{s}$.

- [GR9], where $G = \mathbf{p} \rightsquigarrow_{\mathbf{t}} \mathbf{q} : j : \{l_i : G_i\}_{i \in I}$,

and $G' = \mathbf{p} \rightsquigarrow_{\mathbf{t}} \mathbf{q} : j : \{l_i : G'_i\}_{i \in I}$.

By hypothesis, $G_j \xrightarrow{l} G'_j$,

$\forall i \in I \setminus \{j\}. G'_i = G_i$, and $\mathbf{q} \neq \text{subj}(l)$.

If $G \uparrow \mathbf{r}$ exists, so does $G_i \uparrow \mathbf{r}$ for $i \in I$.

By assumption, $G \otimes \mathbf{s}$, so $\mathbf{t} = \mathbf{s} \wedge G_j \otimes \mathbf{s}$.

By induction on $G_j \xrightarrow{l} G'_j$ and hypothesis $\forall i \in I \setminus \{j\}. G'_i = G_i$, we get $\forall i \in I. (G'_i \uparrow \mathbf{r} \text{ exists } \wedge G'_i \otimes \mathbf{s})$.

(1). To show $G' \uparrow \mathbf{r}$, consider \mathbf{r} by case:

- $\mathbf{r} = \mathbf{p}$: Then $G' \uparrow \mathbf{p} = G'_j \uparrow \mathbf{p}$.
- $\mathbf{r} = \mathbf{q}$: Then $G' \uparrow \mathbf{q} = \mathbf{p} \& \langle \mathbf{s} \rangle \{l_i : G'_i \uparrow \mathbf{q}\}_{i \in I}$.
- $\mathbf{r} = \mathbf{s}$: Then $G' \uparrow \mathbf{s} = \mathbf{p} \hookrightarrow \mathbf{q} : j : \{l_i : G'_i \uparrow \mathbf{s}\}_{i \in I}$.
- $\mathbf{r} \notin \{\mathbf{p}, \mathbf{q}, \mathbf{s}\}$: Then $G' \uparrow \mathbf{r} = G'_j \uparrow \mathbf{r}$.

(2). We have $\mathbf{t} = \mathbf{s}$ from assumption and $G'_j \otimes \mathbf{s}$ from induction,

so $G' \otimes \mathbf{s}$. □

Lemma C.12 (Progress for Well-formed Global Types). *Let G be a global type. Suppose G is well-formed with respect to some router \mathbf{s} , i.e. $\text{wellFormed}^R(G, \mathbf{s})$.*

$$(G = \text{end}) \vee \exists G', l. (G \xrightarrow{l} G')$$

Proof. The following is logically equivalent:

$$(G \neq \text{end}) \implies \exists G', l. (G \xrightarrow{l} G').$$

We prove this by induction on the structure of G .

We do not consider $G = \text{end}$ by assumption.

We do not consider $G = \mathbf{t}$ as the type variable occurs free.

1. $G = \mu \mathbf{t}. G''$

\mathbf{t} must occur in G , so $G[\mu \mathbf{t}. G/\mathbf{t}] \neq \text{end}$.

By induction, $\exists G', l. (G[\mu \mathbf{t}. G/\mathbf{t}] \xrightarrow{l} G')$.

Apply [GR3] to get $\exists G', l. (\mu \mathbf{t}. G \xrightarrow{l} G')$.

2. $G = \mathbf{p} \rightarrow \mathbf{q} : \{l_i : G_i\}_{i \in I}$

Apply [GR1] to get $G \xrightarrow{\mathbf{p} \mathbf{q} ! j} \mathbf{p} \rightsquigarrow \mathbf{q} : j : \{l_i : G_i\}_{i \in I}$.

3. $G = \mathbf{p} \dashv \mathbf{r} \rightarrow \mathbf{q} : \{l_i : G_i\}_{i \in I}$

By assumption, $\text{wellFormed}^R(G, \mathbf{s})$, so $\mathbf{r} = \mathbf{s}$.

Apply [GR6] to get $G \xrightarrow{\text{via}(\mathbf{s})(\mathbf{p} \mathbf{q} ! j)} \mathbf{p} \rightsquigarrow_{\mathbf{s}} \mathbf{q} : j : \{l_i : G_i\}_{i \in I}$.

4. $G = \mathbf{p} \rightsquigarrow \mathbf{q} : j : \{l_i : G_i\}_{i \in I}$

Apply [GR2] to get $G \xrightarrow{\mathbf{p} \mathbf{q} ? j} G_j$.

5. $G = \mathbf{p} \rightsquigarrow_{\mathbf{r}} \mathbf{q} : j : \{l_i : G_i\}_{i \in I}$

By assumption, $\text{wellFormed}^R(G, \mathbf{s})$, so $\mathbf{r} = \mathbf{s}$.

Apply [GR7] to get $G \xrightarrow{\text{via}(\mathbf{s})(\mathbf{p} \mathbf{q} ? j)} G_j$. □

Proof of Theorem 4.11.

Let G be a global type, and \mathbf{s} be a role. Then we have:
 $\text{wellFormed}(G) \iff \text{wellFormed}^R(\llbracket G, \mathbf{s} \rrbracket, \mathbf{s})$

Proof. (\implies) Direct consequence of Lemmas C.3 and C.9

(\impliedby) By definition. □

C.4 Proof of Theorem 4.12

Let G, G' be well-formed global types such that $G \xrightarrow{l} G'$ for some label l . Then we have:

$$\forall l, \mathbf{s}. \left(G \xrightarrow{l} G' \iff \llbracket G, \mathbf{s} \rrbracket \xrightarrow{\llbracket l, \mathbf{s} \rrbracket} \llbracket G', \mathbf{s} \rrbracket \right)$$

Proof. By rule induction on $G \xrightarrow{l} G'$. Take arbitrary router role \mathbf{s} .

- [GR1], where $G = \mathbf{p} \rightarrow \mathbf{q} : \{l_i : G_i\}_{i \in I}$,

$G' = \mathbf{p} \rightsquigarrow \mathbf{q} : j : \{l_i : G_i\}_{i \in I}$,

and $l = \mathbf{p} \mathbf{q} ! j$.

To show $\llbracket G, \mathbf{s} \rrbracket \xrightarrow{\llbracket l, \mathbf{s} \rrbracket} \llbracket G', \mathbf{s} \rrbracket$, consider \mathbf{s} by case:

- $\mathbf{s} \in \{\mathbf{p}, \mathbf{q}\}$: Then we have

$$\llbracket G, \mathbf{s} \rrbracket = \mathbf{p} \rightarrow \mathbf{q} : \{l_i : \llbracket G_i, \mathbf{s} \rrbracket\}_{i \in I}$$

$$\llbracket G', \mathbf{s} \rrbracket = \mathbf{p} \rightsquigarrow \mathbf{q} : j : \{l_i : \llbracket G_i, \mathbf{s} \rrbracket\}_{i \in I}$$

$$\llbracket l, \mathbf{s} \rrbracket = \mathbf{p} \mathbf{q} ! j$$

The encoded transition is possible using [GR1].

- $\mathbf{s} \notin \{\mathbf{p}, \mathbf{q}\}$: Then we have

$$\llbracket G, \mathbf{s} \rrbracket = \mathbf{p} \dashv \mathbf{r} \rightarrow \mathbf{q} : \{l_i : \llbracket G_i, \mathbf{s} \rrbracket\}_{i \in I}$$

$$\llbracket G', \mathbf{s} \rrbracket = \mathbf{p} \rightsquigarrow_{\mathbf{s}} \mathbf{q} : j : \{l_i : \llbracket G_i, \mathbf{s} \rrbracket\}_{i \in I}$$

$$\llbracket l, \mathbf{s} \rrbracket = \text{via}(\mathbf{s})(\mathbf{p} \mathbf{q} ! j)$$

The encoded transition is possible using [GR6].

- [GR2], where $G = \mathbf{p} \rightsquigarrow \mathbf{q} : j : \{l_i : G_i\}_{i \in I}, G' = G_j, l = \mathbf{p} \mathbf{q} ? j$.

We know $\llbracket G', \mathbf{s} \rrbracket = \llbracket G_j, \mathbf{s} \rrbracket$

To show $\llbracket G, \mathbf{s} \rrbracket \xrightarrow{\llbracket l, \mathbf{s} \rrbracket} \llbracket G', \mathbf{s} \rrbracket$, consider \mathbf{s} by case:

- $\mathbf{s} \in \{\mathbf{p}, \mathbf{q}\}$: Then we have

$$\llbracket G, \mathbf{s} \rrbracket = \mathbf{p} \rightsquigarrow \mathbf{q} : j : \{l_i : \llbracket G_i, \mathbf{s} \rrbracket\}_{i \in I}$$

$$\llbracket l, \mathbf{s} \rrbracket = \mathbf{p} \mathbf{q} ? j$$

The encoded transition is possible using [GR2].

- $\mathbf{s} \notin \{\mathbf{p}, \mathbf{q}\}$: Then we have

$$\llbracket G, \mathbf{s} \rrbracket = \mathbf{p} \dashv_{\mathbf{s}} \mathbf{q} : j : \{l_i : \llbracket G_i, \mathbf{s} \rrbracket\}_{i \in I}$$

$$\llbracket l, \mathbf{s} \rrbracket = \text{via}(\mathbf{s})(\mathbf{p} \mathbf{q} ? j)$$

The encoded transition is possible using [GR7].

- [GR3], where $G = \mu \mathbf{t}. G''$.

By hypothesis, $G''[\mu \mathbf{t}. G''/\mathbf{t}] \xrightarrow{l} G'$.

By induction, $\llbracket G''[\mu \mathbf{t}. G''/\mathbf{t}], \mathbf{s} \rrbracket \xrightarrow{\llbracket l, \mathbf{s} \rrbracket} \llbracket G', \mathbf{s} \rrbracket$.

By Lemma C.4, $\llbracket G''[\mu \mathbf{t}. G''/\mathbf{t}], \mathbf{s} \rrbracket = \llbracket G'', \mathbf{s} \rrbracket [\mu \mathbf{t}. \llbracket G'', \mathbf{s} \rrbracket / \mathbf{t}]$.

We know $\llbracket G, \mathbf{s} \rrbracket = \llbracket \mu \mathbf{t}. G'', \mathbf{s} \rrbracket = \mu \mathbf{t}. \llbracket G'', \mathbf{s} \rrbracket$.

The encoded transition is possible using [GR3] as shown:

$$\frac{\llbracket G'', s \rrbracket \xrightarrow{\mu t. \llbracket G'', s \rrbracket / t} \llbracket G', s \rrbracket \xrightarrow{\llbracket l, s \rrbracket} \llbracket G', s \rrbracket}{\mu t. \llbracket G'', s \rrbracket \xrightarrow{\llbracket l, s \rrbracket} \llbracket G', s \rrbracket} \text{ [GR3]}$$

- [GR4], where $G = \mathbf{p} \rightarrow \mathbf{q} : \{l_i : G_i\}_{i \in I}$, $G' = \mathbf{p} \rightarrow \mathbf{q} : \{l_i : G'_i\}_{i \in I}$.

By hypothesis, $\forall i \in I. G_i \xrightarrow{l} G'_i$ and $\text{subj}(l) \notin \{\mathbf{p}, \mathbf{q}\}$.

By induction, $\forall i \in I. \left(\llbracket G_i, s \rrbracket \xrightarrow{\llbracket l, s \rrbracket} \llbracket G'_i, s \rrbracket \right)$.

By definition of $\text{subj}(\cdot)$, $\text{subj}(\llbracket l, s \rrbracket) \notin \{\mathbf{p}, \mathbf{q}\}$.

To show $\llbracket G, s \rrbracket \xrightarrow{\llbracket l, s \rrbracket} \llbracket G', s \rrbracket$, consider s by case:

- $s \in \{\mathbf{p}, \mathbf{q}\}$: Then we have

$$\begin{aligned} \llbracket G, s \rrbracket &= \mathbf{p} \rightarrow \mathbf{q} : \{l_i : \llbracket G_i, s \rrbracket\}_{i \in I} \\ \llbracket G', s \rrbracket &= \mathbf{p} \rightarrow \mathbf{q} : \{l_i : \llbracket G'_i, s \rrbracket\}_{i \in I} \end{aligned}$$

The encoded transition is possible using [GR4].

- $s \notin \{\mathbf{p}, \mathbf{q}\}$: Then we have

$$\begin{aligned} \llbracket G, s \rrbracket &= \mathbf{p} \rightarrow s \rightarrow \mathbf{q} : \{l_i : \llbracket G_i, s \rrbracket\}_{i \in I} \\ \llbracket G', s \rrbracket &= \mathbf{p} \rightarrow s \rightarrow \mathbf{q} : \{l_i : \llbracket G'_i, s \rrbracket\}_{i \in I} \end{aligned}$$

The encoded transition is possible using [GR8].

- [GR5], where $G = \mathbf{p} \rightsquigarrow \mathbf{q} . j : \{l_i : G_i\}_{i \in I}$,
 $G' = \mathbf{p} \rightsquigarrow \mathbf{q} . j : \{l_i : G'_i\}_{i \in I}$.

By hypothesis, $G_j \xrightarrow{l} G'_j$, $\mathbf{p}' \neq \text{subj}(l)$,

and $\forall i \in I \setminus \{j\}. G'_i = G_i$.

By induction, $\llbracket G_j, s \rrbracket \xrightarrow{\llbracket l, s \rrbracket} \llbracket G'_j, s \rrbracket$.

By definition of a set of subjects, we have: $\text{subj}(\llbracket l, s \rrbracket) \neq \mathbf{q}$.

To show $\llbracket G, s \rrbracket \xrightarrow{\llbracket l, s \rrbracket} \llbracket G', s \rrbracket$, consider s by case:

- $s \in \{\mathbf{p}, \mathbf{q}\}$: Then we have

$$\begin{aligned} \llbracket G, s \rrbracket &= \mathbf{p} \rightsquigarrow \mathbf{q} . j : \{l_i : \llbracket G_i, s \rrbracket\}_{i \in I} \\ \llbracket G', s \rrbracket &= \mathbf{p} \rightsquigarrow \mathbf{q} . j : \{l_i : \llbracket G'_i, s \rrbracket\}_{i \in I} \end{aligned}$$

The encoded transition is possible using [GR5].

- $s \notin \{\mathbf{p}, \mathbf{q}\}$: Then we have

$$\begin{aligned} \llbracket G, s \rrbracket &= \mathbf{p} \rightsquigarrow_s \mathbf{q} . j : \{l_i : \llbracket G_i, s \rrbracket\}_{i \in I} \\ \llbracket G', s \rrbracket &= \mathbf{p} \rightsquigarrow_s \mathbf{q} . j : \{l_i : \llbracket G'_i, s \rrbracket\}_{i \in I} \end{aligned}$$

The encoded transition is possible using [GR9].

(\Leftarrow) direction is similar by rule induction on

$$\llbracket G, s \rrbracket \xrightarrow{\llbracket l, s \rrbracket} \llbracket G', s \rrbracket.$$

□

D Appendix for § 5

We include two more studies: Battleships and Travel Agency.

Battleships. We implement the *Battleships* board game between two players, as used by King et al. [20]. The initialisation phase involves both players placing rectangular battleships on a 2D grid. The session proceeds to the game loop, where players take turns to guess the location of their opponent's ships, where the server responds with a hit or a miss. The game loop continues until all ships of one player have been sunk.

```
// Ship configuration
type <typescript> "Config" from "./Models" as Config;
// Coordinate on 2D grid
type <typescript> "Location" from "./Models" as Loc;
global protocol Battleships(role P1, role Svr, role P2) {
  Init(Config) from P1 to Svr;
  Init(Config) from P2 to Svr; do Game(P1, Svr, P2); }
aux global protocol Game(role Atk, role Svr, role Def) {
  Attack(Location) from Atk to Svr;
  choice at Svr
  { // Hit an opposing ship coordinate
    Hit(Loc) from Svr to Atk;
    Hit(Loc) from Svr to Def;
    do Game(Def, Svr, Atk); }
  or { Miss(Loc) from Svr to Atk;
    Miss(Loc) from Svr to Def;
    do Game(Def, Svr, Atk); }
  or { // Hit all coordinates of an opposing ship
    Sunk(Loc) from Svr to Atk;
    Sunk(Loc) from Svr to Def;
    do Game(Def, Svr, Atk); }
  or { // Sunk all opposing ships
    Winner(Loc) from Svr to Atk;
    Loser(Loc) from Svr to Def; } }
```

By interpreting the session ID (generated for **Svr** by STScript) as an unique game identifier, the developer can keep track of concurrent game sessions very easily. As the generated session runtime for Node.js needs to be initialised by a *function* that is parameterised by the game ID and returns the initial state, the game ID is bound inside the closure. This means that the invocation of callbacks (as part of the game logic) can access the game ID of the current game, so the developer can update the application state of the corresponding game.

```
const gameManager = (gameID: string) => {
  const handleP1 = Session.S176({
    Attack: async (Next, location) => {
      // Handle attack by P1 in current game
      const result = await
        DB.attack(gameID, GamePlayers.P1, location);
      ...}, });
  const handleP2 = ... // defined similarly
  return Session.Initial({
    Init: (Next, p1Config) => Next({
      Init: (_, p2Config) => {
        // Initialise new game in database bound to 'gameID'
        DB.initialiseGame(gameID, p1Config, p2Config);
        return handleP1; }, }, }); });
  // Initialise session runtime
  new Svr(webSocketServer, cancellationHandler, gameManager);
```

Because the API for the session cancellation handler also exposes the session ID of the cancelled session, the **Svr** can use the session ID to free up resources allocated to the corresponding game session accordingly. In fact, given that the API also exposes the role that initiated the cancellation, the **Svr** could identify which player forfeited the game and update leaderboard details to reflect the forfeit.

```
const cancellationHandler = async (
```

```

    id: string, role: Role.All, reason: any) => {
    console.log(`${id}: ${role} disconnected - ${reason}`);
    // Free up resources allocated by this game
    await DB.deleteGame(id); });

```

Travel Agency. We implement the Travel Agency scenario motivated in § 1. We specify the Scribble protocol in Fig. 4, and present the STScript APIs implemented by the developer for both server and client endpoints in § 2.

This scenario involves routed communications – namely, between the customer and their friend. In § 3, we discuss how the routing mechanism is transparent to the Node.js callbacks implemented by the developer. Here, we show that the routing mechanism is equally transparent to the React.js components implemented by the developer for browser-side endpoints.

```

export default class WaitSuggestion extends S11 {
  /* ...snip... */
  Suggest(place: string) {
    this.context.setSuggestion(place);
  }
  /* ...snip... */
}

export default class WaitResponse extends S14 {
  /* ...snip... */
  Available(quote: number) {
    this.context.setQuote(quote);
  }

  Full() {
    this.context.setErrorMessage(`
    No availability for ${this.context.suggestion}
    `);
    this.context.setSuggestion('');
  }
  /* ...snip... */
}

```

Focusing on the role **A**, the `WaitSuggestion` component expects a message from the other client role **B**, and the `WaitResponse` component expects to receive from the server role **S**. Because the client roles **A** and **B** cannot directly communicate over a WebSocket connection, the message to be received by `WaitSuggestion` is in fact routed by **S**. However, this is transparent to the developer – both components handle incoming messages in the same manner.

Additionally, the APIs generated by STScript offer developers the flexibility to integrate existing third-party libraries and frameworks when designing their user interfaces. The client endpoints are written using the *Material-UI* framework [22] and leverage the *React Context API* to manage internal application state.

E Code for Travel Agency scenario

This appendix contains the implementation for the Travel Agency scenario (specified in Fig. 4). We walk through key aspects of the APIs generated by STScript are used to implement the role **S** (for the server endpoint) and role **B** (for the client endpoint). The full implementations can be found in the accompanying artifact [23].

E.1 Server Role S: Generated APIs

```

namespace Message
export interface S40_Available {
  label: "Available", payload: [number] };
export interface S40_Full { label: "Full", payload: [] };
export type S40 = | S40_Available | S40_Full;

export interface S38_Query {
  label: "Query", payload: [string] };
export type S38 = | S38_Query;

export interface S41_Confirm {
  label: "Confirm", payload: [Cred] };
export interface S41_Reject { label: "Reject", payload: [] };
export type S41 = | S41_Confirm | S41_Reject;

EFSM state transitions are characterised by the possible messages
to be sent or received. We generate an interface for each message,
specifying types for the label (as a string literal) and payload (as
defined on the protocol). Hence, each state is defined as a union
type of the possible messages.

namespace Handler
export type S40 = MaybePromise<
  | ["Available", Message.S40_Available['payload'], State.S41]
  | ["Full", Message.S40_Full['payload'], State.S38]>;

export interface S38 {
  "Query": (Next: typeof Factory.S40,
    ...payload: Message.S38_Query['payload']
  ) => MaybePromise<State.S40>, };

export interface S41 {
  "Confirm": (Next: typeof Factory.S39,
    ...payload: Message.S41_Confirm['payload']
  ) => MaybePromise<State.S39>,
  "Reject": (Next: typeof Factory.S39,
    ...payload: Message.S41_Reject['payload']
  ) => MaybePromise<State.S39>, };

```

Handlers define the callback-style APIs that the developer needs to implement. The handler for a *send state* (i.e. `S40`) is a tuple of the message label (as a string literal), payload, and the successor state. The handler for a *receive state* (i.e. `S38`, `S41`) is an object literal defining labelled callbacks. Each callback is parameterised by a factory function for the successor state (discussed shortly) and the payload for this particular message type, and is expected to return the successor state. The `MaybePromise<>` generic type allows developers to write *asynchronous* handlers in their implementation.

```

namespace State
interface ISend {
  readonly type: 'Send';
  performSend(next: StateTransitionHandler,
    cancel: Cancellation, send: SendStateHandler): void; };

interface IReceive {
  readonly type: 'Receive';
  prepareReceive(next: StateTransitionHandler,

```

```

cancel: Cancellation,
register: ReceiveStateHandler): void; };

interface ITerminal { readonly type: 'Terminal'; };

export type Type = ISend | IReceive | ITerminal;

export class S40 implements ISend {
  readonly type: 'Send' = 'Send';
  constructor(public handler: Handler.S40) { }

  performSend(next: StateTransitionHandler,
  cancel: Cancellation, send: SendStateHandler) {
    const thunk = (
      [label, payload, succ]: FromPromise<Handler.S40>) => {
      send(Role.Peers.A, label, payload);
      return next(succ); };
    if (this.handler instanceof Promise) {
      this.handler.then(thunk).catch(cancel); }
    else { try { thunk(this.handler); }
      catch (error) { cancel(error); } } } } } }

export class S38 implements IReceive {
  readonly type: 'Receive' = 'Receive';
  constructor(public handler: Handler.S38) { }

  prepareReceive(next: StateTransitionHandler,
  cancel: Cancellation, register: ReceiveStateHandler) {
    const onReceive = (message: any) => {
      const parsed = JSON.parse(message) as Message.S38;
      switch (parsed.label) {
        case "Query": { try {
          const successor = this.handler[parsed.label](
            Factory.S40, ...parsed.payload);
          if (successor instanceof Promise) {
            successor.then(next).catch(cancel); }
          else { next(successor); }
        } catch (error) { cancel(error); }
        return; } } } } } }
    register(Role.Peers.A, onReceive); } } } }

```

The handler for each EFSM state is used to instantiate its State class instance, which is used by the session runtime to trigger the communication action. For *send states*, the runtime triggers the performSend method (Line 20) to perform the send using the label and payload defined in the handler (Line 24). For *receive states*, the State class instance registers the handler to the runtime, so the handler can be invoked when the message is received. The State class will check whether the handler is defined asynchronously (i.e. a TypeScript Promise) and invoke the handler accordingly.

namespace Factory

```

type S40_Available =
  | [Message.S40_Available['payload'],
    (Next: typeof S41) => State.S41]
  | [Message.S40_Available['payload'], State.S41];

function S40_Available(
  payload: Message.S40_Available['payload'],

```

```

  generateSucc: (Next: typeof S41) => State.S41): State.S40;
function S40_Available(
  payload: Message.S40_Available['payload'],
  succ: State.S41): State.S40;
function S40_Available(...args: S40_Available) {
  if (typeof args[1] === 'function') {
    const [payload, generateSucc] = args;
    const succ = generateSucc(S41);
    return new State.S40(["Available", payload, succ]); }
  else {
    const [payload, succ] = args;
    return new State.S40(["Available", payload, succ]); } }

type S40_Full =
  | [Message.S40_Full['payload'],
    (Next: typeof S38) => State.S38]
  | [Message.S40_Full['payload'], State.S38];

// function S40_Full defined similarly

export const S40 = {
  Available: S40_Available, Full: S40_Full, };

export function S38(handler: Handler.S38) {
  return new State.S38(handler); };
export function S41(handler: Handler.S41) {
  return new State.S41(handler); };

export const Initial = S38;

export const S39 = () => new State.S39();
export const Terminal = S39;

```

The Factory namespace exposes *developer-friendly* APIs for instantiating the State class instance. The factory API for a *send state* is an object literal defining labelled callbacks for each possible selection. Each callback is parameterised by the message payload and successor state. The factory API for a *receive state* is an alias for the constructor function of the corresponding State class. Initial and Terminal aliases are also exported as convenient references to the initial and terminal EFSM state respectively.

E.2 Server Role S: API Usage

```

import express from "express";
import http from "http";
import WebSocket from "ws";

const app = express();
const server = http.createServer(app);
const wss = new WebSocket.Server({ server });

import { Session, S } from "../TravelAgency/S";

const agencyProvider = (sessionID: string) => {
  const handleQuery = Session.Initial({
    Query: async (Next, dest) => {
      const res = await checkAvailability(sessionID, dest);
      if (res.status === "available") {

```



```

    return Next.Available([res.quote], handleResponse); }
    else { return Next.Full([], handleQuery); },,));

const handleResponse = Session.S41({
  Confirm: async (End, credentials) => {
    // Handle confirmation
    await confirmBooking(sessionID, credentials);
    return End(); },
  Reject: async (End) => {
    await release(sessionID);
    return End(); },,});
return handleQuery; };

new S(wss, async (sessionID, role, reason) => {
  if (role === Role.Self) {
    console.error(`${sessionID}: internal server error`); }
  else { await tryRelease(sessionID); },, agencyProvider);

```

The developer instantiates the session (Line 29) using the WebSocket server, cancellation handler, and the EFSM implementation — a function to be invoked for every new session, parameterised by the session ID, and returns the State class instance of the initial state. Line 12 implements the API generated for a receive state, specifying how to handle a Query message. Line 16 implements the API generated for a send state — send the Available message with the price and proceed to the handleResponse continuation.

E.3 Client Role B: Generated APIs

```

src/TravelAgency/B/S27.tsx

type Props = { factory: SendComponentFactoryFactory };
export default abstract class S27<ComponentState = {}>
  extends React.Component<Props, ComponentState> {
  protected Suggest: SendComponentFactory<[string]>;
  constructor(props: Props) {
    super(props);
    this.Suggest = props.factory<[string]>(
      Roles.Peers.A, 'Suggest', ReceiveState.S29); }

```

The generated React component for a *send state* receives a factory function from the session runtime to generate *component factories* for each permitted selection. Line 7 reads, “generate a component factory which sends a message (labelled Suggest to role A with one string-typed payload) and transitions to state S29”. The component factory is defined as a *protected* property to allow access by subclasses implemented by the developer.

```

src/TravelAgency/B/S29.tsx

enum Labels { Quote = 'Quote', Full = 'Full' };

interface QuoteMessage {
  label: Labels.Quote, payload: [number] };
interface FullMessage {
  label: Labels.Full, payload: [] };
type Message = | QuoteMessage | FullMessage

type Props = {
  register: (role: Roles.Peers,
    handle: ReceiveHandler) => void };

```

```

export default abstract class S29<ComponentState = {}>
  extends React.Component<Props, ComponentState> {
  componentDidMount() {
    this.props.register(Roles.Peers.A,
      this.handle.bind(this)); }

  handle(data: any): MaybePromise<State> {
    const message = JSON.parse(data) as Message;
    switch (message.label) {
    case Labels.Quote: {
      const thunk = () => SendState.S30;
      const continuation = this.Quote(...message.payload);
      if (continuation instanceof Promise) {
        return new Promise((resolve, reject) => {
          continuation.then(() => resolve(thunk()))
            .catch(reject); }); }
      else { return thunk(); } }
    case Labels.Full: {
      const thunk = () => SendState.S27;
      const continuation = this.Full(...message.payload);
      if (continuation instanceof Promise) {
        return new Promise((resolve, reject) => {
          continuation.then(() => resolve(thunk()))
            .catch(reject); }); }
      else { return thunk(); } } }

    abstract Quote(payload1: number, ): MaybePromise<void>;
    abstract Full(): MaybePromise<void>; }

```

The generated React component for a *receive state* registers a message handler (Line 19) to the session runtime component, to be invoked on a WebSocket onmessage event. An abstract method is exposed for each possible branch (Lines 39 and 40), requiring the developer to explicitly handle the received message. When invoked, the message handler parses the WebSocket message and invokes the abstract method (implemented by the developer) corresponding to the label of the received message. The message handler returns the successor state to the runtime to advance the EFSM.

E.4 Client Role B: API Usage

```

src/components/MakeSuggestion.tsx

import { S27 } from "../../TravelAgency/B";
export default class MakeSuggestion extends S27 {
  static contextType = FriendState;
  declare context: React.ContextType<typeof FriendState>;

  render() {
    const options: DestinationOption[] = places.map(
      (name) => ({ name,
        buildClickComponent: () => ([ 'Suggest',
          this.Suggest('onClick', () => {
            this.context.setDestination(name);
            this.context.setErrorMessage(undefined);
            return [name]; }),,]),,));
    return (<div>
      <Typography variant='h3' gutterBottom>

```

```

    Offer Suggestion
  </Typography>
  <Container>
    {this.context.errorMessage !== undefined &&
    <Alert
      style={{ marginBottom: '1rem' }}
      severity='error'>
        {this.context.errorMessage}</Alert>
    <Grid container spacing={3}>
      {options.map((option, key) => (
        <Grid item xs={6} sm={4} key={key}>
          <TravelCard content={option} />
        </Grid>))}
    </Grid></Container></div>); }};

```

The developer implements the send state S27 by extending from the corresponding abstract class, and uses the component factory property to generate UI components that are bound to the communication action. Line 10 creates a React component that sends the Suggest message on a click event, for each destination option in places.

WaitResponse.tsx

```

import { S29 } from "../../TravelAgency/B";
export default class WaitResponse extends S29 {
  static contextType = FriendState;
  declare context: React.ContextType<typeof FriendState>;

  Full() {
    this.context.setErrorMessage(
      `No availability for ${this.context.destination}`);
    this.context.setDestination(undefined); }

  Quote(quote: number) { this.context.setQuote(quote); }

  render() {
    return <div>
      <div><Typography variant='h3' gutterBottom>
        Pending enquiry for {this.context.destination}
      </Typography></div>
      <div><CircularProgress /></div>
    </div>); }};

```

The developer implements the receive state S29 by extending from the corresponding abstract class, and implements the required abstract methods to define how to handle a Full message (Line 6) or a Quote message (Line 11).

FriendView.tsx

```

import { B } from "../../TravelAgency/B";

export default class FriendView extends React.Component {
  render() {
    const origin = process.env.REACT_APP_PROXY
    ?? window.location.origin;
    const endpoint = origin.replace(/^http/, 'ws');
    return <div><FriendState>
      <B
        endpoint={endpoint}
        states={{ S27: MakeSuggestion, S28: Completion,

```

```

        S29: WaitResponse, S30: MakeDecision }}
      waiting=<<CircularProgress />
      connectFailed=<<Alert severity='error'>
        Connect Failed</Alert>
      cancellation={(role, reason) => {
        console.error(reason);
        return <Alert severity='error'>
          Session Cancelled by {role}: {reason}</Alert>; }}
    /></FriendState></div>); }};

```

The developer instantiates the session (Line 9) by supplying: the WebSocket endpoint (Line 10), a React component to render whilst waiting (Line 13), a React component to render on a connection failure (Line 14), a function to build a React component to respond to session cancellation (Line 16), and an object literal (Line 11) mapping each EFSM state to the corresponding subclass implemented by the developer.