

Speak Now

Safe Actor Programming with Multiparty Session Types

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Actor languages such as Erlang and Elixir are widely used for implementing scalable and reliable distributed applications, but the informally-specified nature of actor communication patterns leaves systems vulnerable to costly errors such as communication mismatches and deadlocks. *Multiparty session types* (MPSTs) rule out communication errors early in the development process, but until now, the many-sender, single-receiver nature of actor communication has made it difficult for actor languages to benefit from session types.

This paper introduces *Maty*, the first actor language design supporting both *static* multiparty session typing and the full power of actors taking part in *multiple sessions*. *Maty* therefore combines the error prevention mechanism of session types with the scalability and fault tolerance of actor languages. Our main insight is to enforce session typing through a flow-sensitive effect system, combined with an event-driven programming style and first-class message handlers. Using MPSTs allows us to guarantee communication safety: a process will never send or receive an unexpected message, nor will a session get stuck because an actor is waiting for a message that will never be sent. We extend *Maty* to support Erlang-style supervision and cascading failure, and show that this preserves *Maty*'s strong metatheory. We implement *Maty* in Scala using an API generation approach, and demonstrate the expressiveness of our model by implementing a representative sample of the widely-used Savina actor benchmark suite; an industry-supplied factory scenario; and a chat server.

CCS Concepts: • **Software and its engineering** → **Concurrent programming languages**.

Additional Key Words and Phrases: multiparty session types, actor languages, deadlock-freedom

ACM Reference Format:

Simon Fowler and Raymond Hu. 2026. Speak Now: Safe Actor Programming with Multiparty Session Types. *Proc. ACM Program. Lang.* 10, OOPSLA1, Article 159 (April 2026), 28 pages. <https://doi.org/10.1145/3798267>

1 Introduction

Modern digital infrastructure depends on distributed software. Unfortunately, writing distributed software is difficult: developers must reason about a host of issues such as deadlocks, failures, and adherence to complex communication protocols. Actor languages such as Erlang and Elixir, and frameworks like Akka, are popular for writing scalable, resilient systems; Erlang in particular powers the servers of WhatsApp, which has billions of users worldwide. Actor languages support lightweight processes that communicate through asynchronous explicit message passing rather than shared memory, and support robust failure recovery strategies like *supervision hierarchies*.

Nevertheless, actor languages are not a silver bullet: it is still possible—*easy*, even—to introduce subtle communication errors that are difficult to detect, debug, and fix. Examples include waiting for a message that will never arrive, sending a message that cannot be handled, or sending an incorrect payload. *Multiparty session types* (MPSTs) [7, 32] are *types for protocols* and allow us to reason about structured interactions between communicating participants. If each participant

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ACM 2475-1421/2026/4-ART159

<https://doi.org/10.1145/3798267>

typechecks against its session type, then the system is statically guaranteed to correctly implement the associated protocol, in turn catching communication errors before a program is run.

MPSTs therefore offer a tantalising promise for actor languages: by combining the fault-tolerance and ease-of-distribution of actor languages with the correctness guarantees given by MPSTs, users can fearlessly write robust and scalable distributed code, confident in the absence of communication mismatches and deadlocks. Unfortunately, there is a spanner in the works: MPSTs have been primarily studied for *channel-based* languages, which have a significantly different communication model, and current session-typing approaches for actor languages are severely limited in expressiveness: they either overlay a session-based communication discipline, only describe interactions between two participants, or only permit actors to be involved in a single session at a time. Other behavioural type systems for actors struggle to capture *structured* interactions and *handle failure* effectively.

In this paper we present *Maty*, the first actor language that supports statically-checked multiparty session types and failure handling, combining the error prevention mechanism of session types and the scalability and fault tolerance of actor languages. Our key insight is to adopt an *event-driven programming style* and enforce session typing through a *flow-sensitive effect system*.

1.1 Actor Languages

Actor languages and frameworks are inspired by the *actor model* [2, 31], where an actor reacts to incoming messages by spawning new actors, sending a finite number of messages to other actors, and changing the way it reacts to future messages. Figure 1 shows an Akka implementation of an ID server that generates a fresh ID for every client request.

```
def idServer(count: Int):
  Behavior[IDRequest] = {
    Behaviors.receive { (context, message) =>
      message.replyTo ! IDResponse(count)
      idServer(count + 1)
    }
  }
```

Fig. 1. ID Server

these two roles, but there are key problems implementing and verifying even this simple example in standard MPST frameworks. First, actor programming is inherently *reactive*: computation is driven by the reception of a new message, and actors must be able to respond to requests from a *statically-unknown* number of clients. Second, each response depends on some common *state*.

```
def idServer(count: Int, locked: Boolean):
  Behavior[IDServerRequest] = {
    Behaviors.receive { (context, message) =>
      message match {
        case IDRequest(replyTo) =>
          if (locked) {
            replyTo ! Unavailable()
            idServer(count, locked)
          } else {
            replyTo ! IDResponse(count)
            idServer(count + 1, locked)
          }
        case LockRequest(replyTo) =>
          if (locked) {
            replyTo ! Unavailable()
            idServer(count, locked)
          } else {
            replyTo ! Locked(context.self)
            idServer(count, true)
          }
        case Unlock() =>
          idServer(count, false)
      }
    }
  }
```

Fig. 2. ID Server extended with locking

Introducing any method to synchronise shared state between these processes, be it through an

The `idServer` function records the current request count as its state, and responds to an incoming `IDRequest` by sending the current count before recursing with an incremented request counter.

It is straightforward to specify the client-server *protocol* for this example as a session *type* between

these two roles, but there are key problems implementing and verifying even this simple example in standard MPST frameworks. First, actor programming is inherently *reactive*: computation is driven by the reception of a new message, and actors must be able to respond to requests from a *statically-unknown* number of clients. Second, each response depends on some common *state*.

Classical MPSTs are instead based on session π -calculus, which is effectively a model of *proactive multithreading* as opposed to reactive event handling. A standard MPST server process relies on *replication* to spawn a separate (π -calculus) process to handle each client session concurrently. For reference, common notations/patterns include $\text{Server} = a(x).(P_{\text{thread}}(x) \mid \text{Server})$ or $\text{Server} = !a(x).P_{\text{thread}}(x)$. This model has no direct support for coordinating a *dynamically varying* number of separate client-handler processes, and—crucially—key safety properties of standard MPSTs such as deadlock-freedom **only hold when each process engages in a single session and each session can be conducted fully independently from the others** (i.e., an embarrassingly parallel situation).

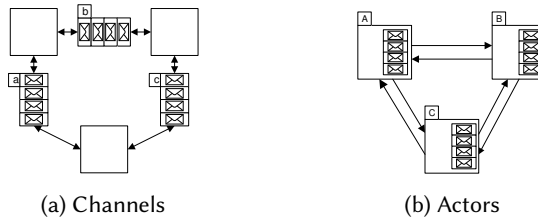


Fig. 3. Channel- and actor-based languages [26]

intricate web of additional internal sessions or some out-of-band (i.e., non-session-typed) method, means deadlock-freedom is no longer guaranteed. Besides safety concerns, the π -calculus based model makes it difficult to express important patterns such as a *single* process waiting to reactively receive from senders across multiple sessions, since inputs are normally blocking operations.

A locking ID server. Figure 2 shows a simple extension of our ID server, where a participant can choose to *lock* the server to prevent it from generating fresh IDs until the lock is released.

In this example, replies depend on whether the ID server is locked. Upon receiving an IDRequest message, if the server is locked, then it will respond with Unavailable; otherwise, it will reply as before. If an unlocked server receives a LockRequest message, it responds with Locked and sets the locked flag. A subsequent Unlock message resets the locked flag.

This small extension to the example reveals some intricacies: once a client has received a lock, it is in a *different state of the protocol* to the remaining clients. First, there is no straightforward way of guaranteeing that the client ever sends an Unlock message, nor that the Unlock message was sent by the same actor that acquired the lock. Second, the server must *always* be able to handle an Unlock message, *even when it is already unlocked*—permitting an invalid state. Both of these issues can be straightforwardly solved using session types in Maty.

1.2 Channels vs. Actors

Session types were originally developed for channel-based languages like Go and Concurrent ML (Figure 3a) and support anonymous processes that communicate over *channel endpoints* using either *synchronous* or *asynchronous* communication. In actor languages (Figure 3b) such as Erlang or Elixir, *named* processes send messages directly to each others' mailboxes. The difference in communication models has significant consequences for distribution and typing. We can easily give a channel endpoint a precise type, e.g., `Chan(Int)` or a *session type* such as `!Int.!Int.?Bool.end` to state that the channel should be used to send two integers and receive a Boolean. Efficiently implementing channels in a distributed setting requires us to store buffered data at the same location that it is processed, but difficulties arise when sending channel endpoints as part of a message (known as *distributed delegation*). Furthermore, implementing even basic channel idioms such as choosing between multiple channels requires complex distributed algorithms [12]. In short, channel-based languages are *easy to type* but *difficult to distribute*.

In contrast, actor languages are much easier to distribute, since every message will always be stored at the process that will handle it. But typing an actor is harder, requiring large variant types, and behavioural typing is difficult since we can only *send* to process IDs and *receive* from mailboxes. Thus, actors are *easy to distribute* but *difficult to type*.

1.3 Key Principles

For session types to be useful for real-world actor programs, we argue that a programming model and session type discipline must satisfy the following *key principles*:

- (KP1) Reactivity** Following the actor model, frameworks like Akka, and Erlang behaviours like `gen_server`, computation should be triggered by incoming messages.
- (KP2) No Explicit Channels** Channel-based languages impose a significantly different programming style, so the programming model should *not* expose explicit channels to a developer.
- (KP3) Multiple Sessions** Actors must be able to simultaneously take part in an unbounded and statically-unknown number of sessions, in order to support server applications. It must be possible for different participants to be at different states of a protocol.
- (KP4) Interaction Between Sessions** Much like our ID server example, interactions in one session should be able to affect the behaviour of an actor in other sessions.
- (KP5) Failure Handling and Recovery** The programming model and type discipline should support failure recovery via supervision hierarchies.

No previous work that applies session types to actor languages satisfies all of the key principles above. Mostrous and Vasconcelos [45] investigated session typing for Core Erlang: their approach emulated session-typed channels by tagging messages with unique references. Their approach was unimplemented, not reactive, exposed a channel-based discipline, and does not support failure, violating **KP1, 2, 5**. Francalanza and Tabone [27] implemented a binary session typing system for Elixir, but their approach is limited to typing interactions between isolated pairs of processes and is therefore severely limited in expressiveness, violating **KP1, 3, 4, 5**. Harvey et al. [30] used multiparty session types in an actor language to support safe runtime adaptation, but each actor can only take part in a *single session* at a time. It is therefore difficult to write server applications and so the language *does not support general-purpose actor programming*, violating **KP1, 3, 4**.

Neykova and Yoshida [48] and Fowler [22] implement programming frameworks closer to following our key principles: each actor is programmed in a reactive style and can be involved in multiple sessions, but both works use *dynamic verification of actors using session types as a notation for generating runtime monitors*. They do not consider any formalism, session type system, nor metatheoretical guarantees, and so there is a significant gap between their conceptual framework and a concrete static programming language design.

In contrast, Maty supports all of our key principles by reacting to incoming messages rather than having an explicit receive operation (**KP1**); enforcing session typing through a flow-sensitive effect system rather than explicit channel handles (**KP2**); using the reactive design to support interleaved handling of messages from different sessions (**KP3**); supporting interaction between sessions using state and self-messages, with our implementation also supporting an explicit session switching construct (**KP4**); and supporting failures and recovery via supervision hierarchies (**KP5**).

1.4 Contributions

Concretely, we make four specific contributions:

- (1) We introduce Maty, the first actor language fully supporting multiparty session types (§3).
- (2) We show that Maty enjoys a strong metatheory (§4): type preservation (Theorem 4.2) guarantees that an actor will never send or receive an unexpected message; progress (Theorem 4.5) guarantees that processes never get stuck due to waiting for a message that is never sent because of an unsafe protocol design or faulty implementation; and global progress (Corollary 4.13) guarantees that, in a system where all event handlers terminate, communication is always eventually possible in any ongoing session.
- (3) We show how to extend Maty with support for Erlang-style failure handling and process supervision (§5), and prove that this maintains Maty's strong metatheory.

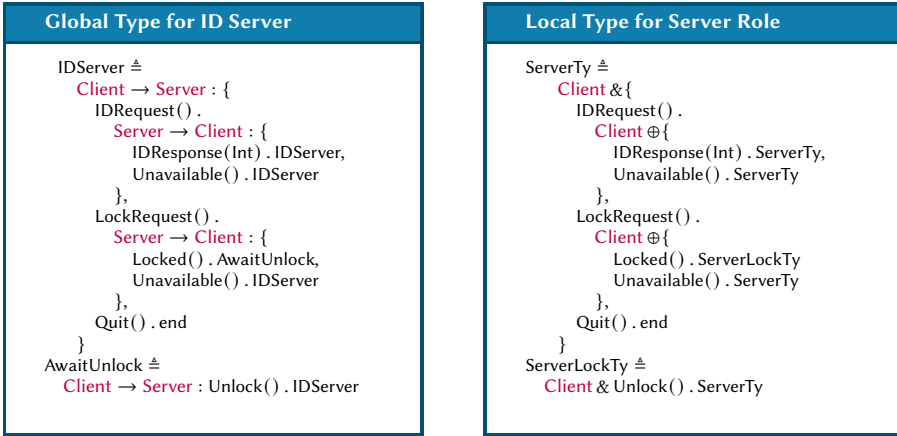


Fig. 4. Session types for the ID server example.

(4) We detail our implementation of Maty using an API generation approach in Scala (§6), and demonstrate our implementation on a representative selection of benchmarks from the Savina actor benchmark suite; a real-world case study from the factory domain; and a chat server. Section 7 discusses related work, and Section 8 concludes.

2 A Tour of Maty

In this section we introduce Maty by example, first by considering how to write our ID server, and then by considering a larger online shop example.

2.1 The Basics: ID Server

Session types. Figure 4 shows the session types for the ID server example. The *global type* describes the interactions between the ID server and a client. For simplicity, we assume a standard encoding of mutually recursive types and use mutually recursive definitions in our examples. The client starts by sending one of IDRequest, LockRequest, or Quit to the server. On receiving IDRequest, the server replies with IDResponse if it is unlocked, or Unavailable if it is locked; in both cases, the protocol then repeats. On receiving LockRequest, the server replies with Locked (if it locks successfully), and the client must then send Unlock before repeating. If already locked, the server responds with Unavailable. The protocol ends when the server receives a Quit message.

A global type can be *projected to local types* that describe the protocol from the perspective of each participant. The local type on the right details the protocol from the server’s viewpoint: the & operator denotes offering a choice, and the ⊕ operator denotes making a selection. The (omitted) ClientTy type is similar, but implements the *dual actions*: where the server offers a choice, the client makes a selection, and vice-versa. We define a *protocol P* as a mapping from role names to local session types. In our example we define IDServerProtocol ≜ {Client : ClientTy, Server : ServerTy}.

Programming model. The Maty programming model is as follows:

- Maty is faithful to the actor model, which has a single thread of execution per actor. This allows access to shared state *without* needing concurrency control mechanisms like mutexes.
- An actor registers with an *access point* to register to take part in a session.
- Once a session is established, the actor can send messages according to its session type. The actor maintains some *actor-level state* and its thread must either return an updated state (if it has completed its part in the protocol), or suspend by installing a *message handler* (if it is

```

idServer : (AP(IDServerProtocol) × (Int × Bool))
  → (Int × Bool)
idServer = λ(ap, state). registerAgain ap; state
registerAgain : (AP(IDServerProtocol)) → Unit
registerAgain = λap.
  register ap Server
    (λst. registerAgain ap; suspend requestHandler st)
unlockHandler : Handler(ServerLockTy, (Int × Bool))
unlockHandler =
  handler Client st {
    Unlock() ↦
      let (curID, locked) = st in
        suspend requestHandler (curID, false)
  }
main : Unit
main =
  let idServerAP = newAP[IDServerProtocol] in
  spawn (idServer (idServerAP, (0, false)));
  spawn (client idServerAP)

requestHandler : Handler(ServerTy, (Int × Bool))
requestHandler =
  handler Client st {
    IDRequest() ↦
      let (curID, locked) = st in
      if locked then
        Client ! Unavailable();
        suspend requestHandler st
      else
        Client ! IDResponse (curID);
        suspend requestHandler (curID + 1, locked),
    LockRequest() ↦
      let (curID, locked) = st in
      if locked then
        Client ! Unavailable();
        suspend requestHandler st
      else
        Client ! Locked();
        suspend unlockHandler (curID, true),
    Quit() ↦ st
  }

```

Fig. 5. Maty implementation of ID Server

ready to receive a message). Suspension acts as a *yield point* to the event loop, and occurs at **precisely the same point as in mainstream actor languages**.

- The event loop can then invoke other installed handlers for any messages in its mailbox—**this is the key mechanism that allows Maty to support multiple sessions**.

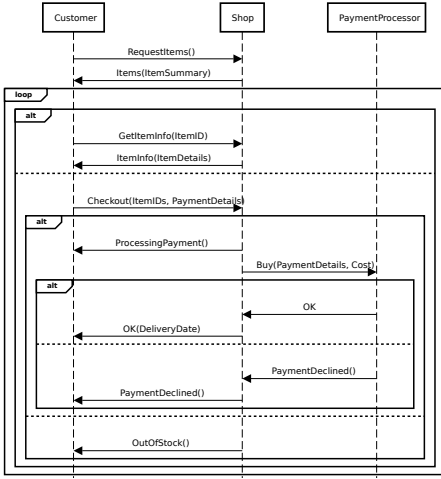
Implementing the ID server. Figure 5 shows an implementation of the ID server in Maty; we allow ourselves the use of mutually-recursive definitions, taking advantage of the usual encoding into anonymous recursive functions. Although we use an effect system that annotates function arrows, we omit effect annotations where they are not necessary.

The server maintains actor-level state of type $(\text{Int} \times \text{Bool})$, containing the current ID and a flag recording whether the server is locked. The `idServer` function takes an *access point* [28] and initial state as an argument, and registers for the **Server** role. An access point can be thought of as a “matchmaking service”: actors *register* to play a role in a session, and the access point establishes a session once actors have registered for each role. The **register** construct takes three arguments: an access point, a role, and a callback to be invoked when the session is established. *Once the callback is invoked, the actor can perform session communication actions for the given role*: in this case, the actor can communicate according to the `ServerTy` type, namely receiving the initial item request from a client. The callback first recursively registers to be involved in future sessions, and then *suspends* awaiting a message from a client, by installing `requestHandler`.

A *message handler* (or simply *handler*) is a first-class construct that describes how an actor handles an incoming message: each handler takes the role to receive from; a variable to which to bind the current actor state; and a series of branches that detail how each message should be handled. An actor *installs* a message handler for the current session by invoking the **suspend** construct, which reverts the actor back to being idle with an updated state, and indicates that the given handler should be invoked when a message is received from the **Client**.

The `requestHandler` has type `Handler(ServerTy, (Int × Bool))`: handlers are parameterised by an input session type and the type of the actor’s state. The handler has three branches, one for each

Scenario Description



- A **Shop** can serve many **Customers** at once.
- The **Customer** begins by requesting a list of items from the **Shop**, which sends back a list of pairs of an item’s identifier and name.
- The **Customer** can then repeatedly either request full details (including description and cost) of an item, or proceed to checkout.
- To check out, the **Customer** sends their payment details and a list of item IDs to the **Shop**.
- If any items are out of stock, then the **Shop** notifies the customer who can then try again. Otherwise, the **Shop** notifies the **Customer** that it is processing the payment, and forwards the payment details and total cost to the **Payment Processor**.
- The **Payment Processor** responds to the **Shop** with whether the payment was successful.
- The **Shop** relays the result to the **Customer**, with a delivery date if the purchase was successful.

Local Types for Shop role

```

ShopTy ≜
  Customer & requestItems() .
  Customer ⊕ items([ (ItemID × ItemName) ]) .
  ReceiveCommand

PaymentResponse ≜
  PaymentProcessor & {
    ok() .
    Customer ⊕ ok(DeliveryDate) .
    ReceiveCommand,
    paymentDeclined() .
    Customer ⊕ paymentDeclined() .
    ReceiveCommand
  }
    
```

```

ReceiveCommand ≜
  Customer & {
    getItemInfo(ItemID) .
    Customer ⊕ itemInfo(Description) .
    ReceiveCommand,
    checkout([ (ItemID × PaymentDetails) ]) .
    Customer ⊕ {
      paymentProcessing() .
      PaymentProcessor ⊕
        buy((PaymentDetails × Price)) .
        PaymentResponse,
      outOfStock() .
      Customer ⊕ outOfStock() .
      ReceiveCommand
    }
  }
    
```

Fig. 6. Online Shop Scenario

possible incoming message. Maty uses a flow-sensitive effect system [3, 21, 29] to enforce session typing using pre- and post-conditions on expressions. In the `IDRequest` branch, the pre-condition `Client ⊕ {IDResponse(Int) . ServerTy, Unavailable() . ServerTy}` means that the actor can *only send IDResponse or Unavailable messages*; all other communication actions are rejected statically. After either message is sent, the session type advances to `ServerTy`, allowing the handler to suspend recursively. The `LockRequest` branch works similarly; since `suspend` aborts the current evaluation context, both branches can be given type `(Int × Bool)` with post-condition `end` to match the `Quit` branch. The `unlockHandler` handles `Unlock` by updating the state, reinstalling `requestHandler`, and suspending. Implementing a client is similar (details omitted). Finally, `main` sets up the access point (associating `Client` with `ClientTy` and `Server` with `ServerTy`), then spawns `idServer` with a pair of arguments `idServerAP` (to allow the server to register for sessions) and `(0, false)`, its initial state. The `main` function also spawns the client, passing the same access point.

```

itemReqHandler : Handler(ShopTy, [Item])
itemReqHandler ≐
  handler Customer stock {
    requestItems() ↪
      Customer!itemSummary(summary(stock));
      suspend custReqHandler stock }

paymentHandler : [ItemID] →
  Handler(PaymentResponse, [Item])
paymentHandler ≐ λitemIDs.
  handler PaymentProcessor stock {
    ok() ↪
      Customer!ok(deliveryDate(itemIDs));
      suspend custReqHandler stock
    paymentDeclined() ↪
      Customer!paymentDeclined();
      let newStock = increaseStock(itemIDs, stock) in
      suspend custReqHandler newStock }

custReqHandler : Handler(ReceiveCommand, [Item])
custReqHandler ≐
  handler Customer stock {
    getItemInfo(itemID) ↪
      Customer!itemInfo(lookupItem(itemID, stock));
      suspend custReqHandler stock
    checkout((itemIDs, details)) ↪
      if inStock(itemIDs, stock) then
        Customer!paymentProcessing();
        let total = cost(itemIDs, stock) in
        let newStock = decreaseStock(itemIDs, stock) in
        PaymentProcessor!buy((details, total));
        suspend (paymentHandler itemIDs) newStock
      else
        Customer!outOfStock();
        suspend custReqHandler stock }

```

Fig. 7. Implementation of Shop message handlers in Maty

2.2 A Larger Example: A Shop

Our ID server example illustrates key parts of Maty, but involves only two roles. We now consider a larger online shop example (Figure 6) to serve as a running example. Multiple clients interact with a single shop, which connects to an external payment processor. Figure 6 shows the local types for **Shop**; we omit **ClientTy** and **PPTy** for **Client** and **PaymentProcessor**, which follow the same pattern. The global type closely follows the sequence diagram.

Shop message handlers. Figure 7 shows the shop’s message handlers. After spawning, the shop suspends with `itemReqHandler`, awaiting a `requestItems` message. On receipt, it retrieves the current stock from its state, sends a summary to the customer, and installs `custReqHandler`.

The `custReqHandler` handles the `getItemInfo` and `checkout` messages. For `getItemInfo`, the shop sends the item details and suspends recursively. For `checkout`, it checks availability: if all items are in stock, it notifies the customer, updates the stock, sends `buy` to the payment processor, and installs `paymentHandler`; otherwise, it sends `outOfStock` and reinstalls `custReqHandler`.

The `paymentHandler` waits for the processor’s reply: if it receives `ok`, it sends the delivery date; if it instead receives `paymentDeclined`, it restores the previous stock. Both branches reinstall `custReqHandler` to handle future requests.

Tying the example together. Finally, we can show how to establish a session using the Shop actors. Let `CustomerProtocol = {Shop : ShopTy, Client : ClientTy, PaymentProcessor : PPTy}`.

```

main ≐
  let custAP = newAP[CustomerProtocol] in
  spawn (shop (custAP, initialStock));
  spawn (paymentProcessor custAP);
  spawn (customer custAP)

shop ≐ λ(custAP, stock). registerAgain custAP; stock
registerAgain ≐ λcustAP.
  register custAP Shop
  (λst. registerAgain custAP; suspend itemReqHandler st)

```

The shop definition takes the access point and then proceeds to `register` to take part in a session to interact with customers. After each session has been established, the session type for the shop states that it needs to receive a message from a client, so the shop suspends with `itemReqHandler`.

Syntax of terms

Roles	p, q	
Variables	x, y, z, f	
Values	V, W	$::= x \mid \lambda x. M \mid \mathbf{rec} f(x). M \mid c \mid (V, W) \mid \mathbf{handler} p \text{ st } \vec{H}$
Handler clauses	H	$::= \ell(x) \mapsto M$
Computations	M, N	$::= \mathbf{let} x = M \mathbf{in} N \mid \mathbf{return} V \mid V W$ $\mid \mathbf{if} V \mathbf{then} M \mathbf{else} N \mid \mathbf{let} (x, y) = V \mathbf{in} M$ $\mid \mathbf{spawn} M \mid p! \ell(V) \mid \mathbf{suspend} V W$ $\mid \mathbf{newAP}[P] \mid \mathbf{register} V p W$

Syntax of types and type environments

Output session types	$S^!$	$::= p \oplus \{\ell_i(A_i). S_i\}_{i \in I}$
Input session types	$S^?$	$::= p \& \{\ell_i(A_i). S_i\}_{i \in I}$
Session types	S, T	$::= S^! \mid S^? \mid \mu X. S \mid X \mid \mathbf{end}$
Protocols	P	$::= \{p_i : S_i\}_{i \in I}$
Types	A, B, C	$::= D \mid A \xrightarrow[C]{S, T} B \mid (A \times B) \mid \mathbf{AP}((p_i : S_i)_{i \in I}) \mid \mathbf{Handler}(S^?, C)$
Base types	D	$::= \mathbf{Unit} \mid \mathbf{Bool} \mid \mathbf{Int} \mid \dots$
Type environments	Γ	$::= \cdot \mid \Gamma, x : A$

Fig. 8. Syntax of terms, types, and type environments

3 Maty: A Core Actor Language with Multiparty Session Types

In this section we introduce Maty formally, giving its syntax, typing rules, and semantics.

3.1 Syntax

Figure 9 shows the syntax of Maty. We let p, q range over roles, and x, y, z, f range over variables. We stratify the calculus into values V, W and computations M, N in the style of *fine-grain call-by-value* [41], with different typing judgements for each.

Session types. Although global types are convenient for describing protocols, we instead follow Scalas and Yoshida [55] and base our formalism around local types (*projection* of global types onto roles is standard [32, 53]; the local types resulting from projecting a global type satisfy the properties that we will see in §4 [55]). *Selection* session types $p \oplus \{\ell_i(A_i). S_i\}_{i \in I}$ indicate that a process can choose to send a message with label ℓ_j and payload type A_j to role p , and continue as session type S_j (assuming $j \in I$). *Branching* session types $p \& \{\ell_i(A_i). S_i\}_{i \in I}$ indicate that a process must *receive* a message. We let $S^!$ range over selection (or *output*) session types, and let $S^?$ range over branching (or *input*) session types. Session type $\mu X. S$ indicates a recursive session type that binds variable X in S ; we take an equi-recursive view of session types and identify each recursive session type with its unfolding. Finally, \mathbf{end} denotes a session type that has finished.

Protocols. A *protocol* P is a collection of roles and their associated session types. Protocols are used when defining access points, and in Section 4 when describing behavioural properties.

Types. Base types D are standard. Since our type system enforces session typing by pre- and post-conditions, a function type $A \xrightarrow[C]{S, T} B$ states that the function takes an argument of type A where the current session type is S , and produces a result of type B with resulting session type T , to be run on an actor with state of type C . An access point has type $\mathbf{AP}((p_i : S_i)_{i \in 1..n})$, mapping each role to a local type. Finally, a message handler has type $\mathbf{Handler}(S^?, A)$ where $S^?$ is an *input* session type and A is the type of the actor state.

Value typing

 $\Gamma \vdash V : A$

$$\frac{\text{TV-VAR} \quad x : A \in \Gamma}{\Gamma \vdash x : A}$$

$$\frac{\text{TV-CONST} \quad c \text{ has base type } D}{\Gamma \vdash c : D}$$

$$\frac{\text{TV-LAM} \quad \Gamma, x : A \mid C \mid S \triangleright M : B \triangleleft T}{\Gamma \vdash \lambda x. M : A \xrightarrow{S, T}_C B}$$

$$\frac{\text{TV-REC} \quad \Gamma, x : A, f : A \xrightarrow{S, T}_C B \mid C \mid S \triangleright M : B \triangleleft T}{\Gamma \vdash \mathbf{rec} f(x). M : A \xrightarrow{S, T}_C B}$$

$$\frac{\text{TV-PAIR} \quad \Gamma \vdash V : A \quad \Gamma \vdash W : B}{\Gamma \vdash (V, W) : (A \times B)}$$

$$\frac{\text{TV-HANDLER} \quad (\Gamma, x_i : A_i, st : C \mid C \mid S_i \triangleright M_i : C \triangleleft \text{end})_{i \in I}}{\Gamma \vdash \mathbf{handler} p \ st \ \{\ell_i(x_i) \mapsto M_i\}_{i \in I} : \text{Handler}(p \ \& \ \{\ell_i(A_i) \cdot S_i\}_{i \in I}, C)}$$

Computation typing

 $\Gamma \mid C \mid S \triangleright M : A \triangleleft T$

$$\frac{\text{T-LET} \quad \Gamma \mid C \mid S_1 \triangleright M : A \triangleleft S_2 \quad \Gamma, x : A \mid C \mid S_2 \triangleright N : B \triangleleft S_3}{\Gamma \mid C \mid S_1 \triangleright \mathbf{let} x = M \mathbf{in} N : B \triangleleft S_3}$$

$$\frac{\text{T-RETURN} \quad \Gamma \vdash V : A}{\Gamma \mid C \mid S \triangleright \mathbf{return} V : A \triangleleft S}$$

$$\frac{\text{T-APP} \quad \Gamma \vdash V : A \xrightarrow{S, T}_C B \quad \Gamma \vdash W : A}{\Gamma \mid C \mid S \triangleright V W : B \triangleleft T}$$

$$\frac{\text{T-LETPAIR} \quad \Gamma \vdash V : (A_1 \times A_2) \quad \Gamma, x : A_1, y : A_2 \mid C \mid S_1 \triangleright M : B \triangleleft S_2}{\Gamma \mid C \mid S_1 \triangleright \mathbf{let} (x, y) = V \mathbf{in} M : B \triangleleft S_2}$$

$$\frac{\text{T-IF} \quad \Gamma \vdash V : \text{Bool} \quad \Gamma \mid C \mid S_1 \triangleright M : A \triangleleft S_2 \quad \Gamma \mid C \mid S_1 \triangleright N : A \triangleleft S_2}{\Gamma \mid C \mid S_1 \triangleright \mathbf{if} V \mathbf{then} M \mathbf{else} N : A \triangleleft S_2}$$

$$\frac{\text{T-SPAWN} \quad \Gamma \mid A \mid \text{end} \triangleright M : A \triangleleft \text{end}}{\Gamma \mid C \mid S \triangleright \mathbf{spawn} M : \text{Unit} \triangleleft S}$$

$$\frac{\text{T-SEND} \quad j \in I \quad \Gamma \vdash V : A_j}{\Gamma \mid C \mid p \oplus \{\ell_i(A_i) \cdot S_i\}_{i \in I} \triangleright p ! \ell_j(V) : \text{Unit} \triangleleft S_j}$$

$$\frac{\text{T-SUSPEND} \quad \Gamma \vdash V : \text{Handler}(S^?, C) \quad \Gamma \vdash W : C}{\Gamma \mid C \mid S^? \triangleright \mathbf{suspend} V W : A \triangleleft S^?}$$

$$\frac{\text{T-NEWAP} \quad \text{comp}((p_i : T_i)_{i \in I})}{\Gamma \mid C \mid S \triangleright \mathbf{newAP}[(p_i : T_i)_{i \in I}] : \text{AP}((p_i : T_i)_{i \in I}) \triangleleft S}$$

$$\frac{\text{T-REGISTER} \quad j \in I \quad \Gamma \vdash V : \text{AP}((p_i : T_i)_{i \in I}) \quad \Gamma \vdash W : A \xrightarrow{T_j, \text{end}}_A A}{\Gamma \mid A \mid S \triangleright \mathbf{register} V p_j W : \text{Unit} \triangleleft S}$$

Fig. 9. Maty Typing Rules

3.2 Typing Rules

Values. Fig. 9 gives the typing rules for Maty. Value typing $\Gamma \vdash V : A$ states that value V has type A under environment Γ . Session typing is enforced by flow-sensitive effect typing (following Harvey et al. [30]) and so we do not need linear types. Typing for variables and constants is standard (we assume constants include the unit value $()$ of type Unit), and typing rules for functions and recursive functions are adapted to include session types. Message handlers specify how to handle incoming messages: TV-HANDLER states that $\mathbf{handler} p \ st \ \{\ell_i(x_i) \mapsto M_i\}_i$ is typable with type $\text{Handler}(p \ \& \ \{\ell_i(A_i) \cdot S_i\}_i, C)$ if each M_i is typable with precondition S_i where the environment is extended with x_i of type A_i and st of type C , and all branches have postcondition end .

Computations. The computation typing judgement has the form $\Gamma \mid C \mid S \triangleright M : A \triangleleft T$, read as “under type environment Γ and evaluating in an actor with state of type C , given session precondition S , term M has type A and postcondition T ”. A let-binding $\mathbf{let} x = M \mathbf{in} N$ evaluates M and binds its result to x in N , with the session postcondition from typing M used as the precondition when typing N (T-LET); note that this is the only evaluation context in the system. The $\mathbf{return} V$ expression is a trivial computation returning value V and has type A if V also has type A (T-RETURN). A function application $V W$ is typable by T-APP provided that the precondition in the function type matches the current precondition, and advances the postcondition to that of the function type. Rule

Runtime syntax

Actor names	a, b
Session names	s
AP names	p
Init. tokens	ι
Runtime names	$\alpha ::= a \mid s \mid p \mid \iota$
Values	$U, V, W ::= \dots \mid p$
Type env.	$\Gamma ::= \dots$
	$\mid \Gamma, p : \text{AP}((p_i : S_i)_i)$
Reduction labels	$l ::= s \mid \tau$

Configurations	$C, \mathcal{D} ::= (\nu\alpha)C \mid C \parallel \mathcal{D}$ $\mid \langle a, \mathcal{T}, \sigma, \rho \mid p(\chi) \mid s \triangleright \delta$
Message queues	$\delta ::= \epsilon \mid (p, q, \ell(V)) \cdot \delta$
Stored handlers	$\sigma ::= \epsilon \mid \sigma, s[p] \mapsto V$
Initialisation states	$\rho ::= \epsilon \mid \rho, \iota \mapsto V$
Thread states	$\mathcal{T} ::= \mathbf{idle}(V) \mid (M)^s[p] \mid M$
Access point states	$\chi ::= (p_i \mapsto \tilde{t}_i)_i$
Evaluation contexts	$\mathcal{E} ::= [] \mid \mathbf{let} x = \mathcal{E} \mathbf{in} M$
Thread contexts	$\mathcal{M} ::= \mathcal{E} \mid (\mathcal{E})^s[p]$
Top-level contexts	$\mathcal{Q} ::= [] \mid ([])^s[p]$

Structural congruence (configurations)

$$C \equiv \mathcal{D}$$

$$C \parallel \mathcal{D} \equiv \mathcal{D} \parallel C \quad C \parallel (\mathcal{D} \parallel \mathcal{D}') \equiv (C \parallel \mathcal{D}) \parallel \mathcal{D}' \quad (\nu\alpha_1)(\nu\alpha_2)C \equiv (\nu\alpha_2)(\nu\alpha_1)C \quad (\nu s)(s \triangleright \epsilon) \parallel C \equiv C$$

$$\frac{\alpha \notin \text{fn}(C)}{C \parallel (\nu\alpha)\mathcal{D} \equiv (\nu\alpha)(C \parallel \mathcal{D})} \quad \frac{p_1 \neq p_2 \vee q_1 \neq q_2}{s \triangleright \sigma_1 \cdot (p_1, q_1, \ell_1(V_1)) \cdot (p_2, q_2, \ell_2(V_2)) \cdot \sigma_2 \equiv s \triangleright \sigma_1 \cdot (p_2, q_2, \ell_2(V_2)) \cdot (p_1, q_1, \ell_1(V_1)) \cdot \sigma_2}$$

Fig. 10. Operational semantics (1)

T-LETPAIR types a pair deconstruction by binding both pair elements in the continuation M . Rule T-IF types a conditional if its condition is of type `Bool` and both continuations have the same return type and postcondition; this design is in keeping with analogous session type systems [27, 30], but by treating **suspend** as a control operator (with an arbitrary return type and postcondition) we can maintain expressiveness by allowing each branch to finish at a different session type.

The **spawn** M construct spawns a new actor that evaluates term M ; rule T-SPAWN states that if the spawned actor supports state type C , then M must also have type C to return the initial state. It must also have pre- and postconditions `end` because the spawned computation is not yet in a session and so cannot communicate. Rule T-SEND types a send computation $p! \ell(V)$ if ℓ is contained within the selection session precondition, and if V has the corresponding type; the postcondition is the session continuation for the specified branch. There is *no receive construct*, since receiving messages is handled by the event loop. Instead, when an actor wishes to receive a message, it must *suspend* itself with updated state W and install a message handler using **suspend** $V W$. The T-SUSPEND rule states that **suspend** $V W$ is typable if the handler is compatible with the current session type precondition and state type; since the computation does not return, it can be given an arbitrary return type and postcondition.

Sessions are initiated using *access points*: we create an access point for a session with roles and types $(p_i : S_i)_i$ using **newAP** $[(p_i : S_i)_i]$, which must be annotated with the set of roles and local types to be involved in the session (T-NEWAP). The rule ensures that the protocol supported by the access point is *compliant*; will describe this further in §4, but at a high level, if a protocol is compliant then it is free of communication mismatches and deadlocks.

An actor can *register* to take part in a session as role p on access point V using **register** $V p W$; function W is a callback to be invoked once the session is established. Rule T-REGISTER ensures that the access point must contain a session type T associated with role p , and since the initiation callback will be evaluated when the session is established, M must be typable under session type T . Since neither **newAP** nor **register** perform any communication, the session types are unaltered.

The typing rules are not syntax-directed due to the rule for T-SUSPEND, however they can be made algorithmic through type annotations or standard type inference techniques.

3.3 Operational Semantics

Runtime syntax. Modelling the concurrent behaviour of Maty processes, requires additional runtime syntax (Fig. 10). Runtime names are identifiers for runtime entities: actor names a identify

actors; session names s identify established sessions; access point names p identify access points; and *initialisation tokens* ι associate entries in an access point with registered initialisation continuations.

We model communication and concurrency through a language of *configurations* (reminiscent of π -calculus processes). A *name restriction* $(\nu\alpha)C$ binds runtime name α in configuration C , and the right-associative parallel composition $C \parallel \mathcal{D}$ denotes configurations C and \mathcal{D} running in parallel.

An actor is represented as a 4-tuple $\langle a, \mathcal{T}, \sigma, \rho \rangle$, where \mathcal{T} is a thread that can either be idle with state V (**idle**(V)); a term M that is not involved in a session; or $(M)^{s[\mathbf{p}]}$ denoting that the actor is evaluating term M playing role \mathbf{p} in session s . An actor is *active* if its thread is M or $(M)^{s[\mathbf{p}]}$ (for some s , \mathbf{p} , and M), and *idle* otherwise. A handler state σ maps endpoints to handlers, which are invoked when an incoming message is received and the actor is idle. The initialisation state ρ maps initialisation tokens to callbacks to be invoked whenever a session is established. Our reduction rules (Figure 11) make use of indexing notation as syntactic sugar for parallel composition: for example, $\langle a_i, \mathcal{T}_i, \sigma_i, \rho_i \rangle_{i \in 1..n}$ is syntactic sugar for the configuration $\langle a_1, \mathcal{T}_1, \sigma_1, \rho_1 \rangle \parallel \cdots \parallel \langle a_n, \mathcal{T}_n, \sigma_n, \rho_n \rangle$.

An access point $p(\chi)$ has name p and state χ , where the state maps roles to sets of initialisation tokens for actors that have registered to take part in the session. Finally, each session s is associated with a queue $s \triangleright \delta$, where δ is a list of entries $(\mathbf{p}, \mathbf{q}, \ell(V))$ denoting a message $\ell(V)$ sent from \mathbf{p} to \mathbf{q} .

Initial configurations. A program M is run by placing it in an *initial configuration* $(\nu a)(\langle a, M, \epsilon, \epsilon \rangle)$.

Structural congruence and term reduction. Structural congruence is the smallest congruence relation defined by the axioms in Figure 10. As with the π -calculus, parallel composition is associative and commutative, and we have the usual scope extrusion rule; we write $\text{fn}(C)$ to refer to the set of free names in a configuration C . We also include a structural congruence rule on queues that allows us to reorder unrelated messages; notably this rule maintains message ordering between pairs of participants. Consequently, the session-level queue representation is isomorphic to a set of queues between each pair of roles. Term reduction $M \longrightarrow_M N$ is standard β -reduction (omitted).

Communication and concurrency. It is convenient for our metatheory to annotate each communication reduction with the name of the session in which the communication occurs, although we sometimes omit the label where it is not relevant. Rule E-SEND describes an actor playing role \mathbf{p} in session s sending a message $\ell(V)$ to role \mathbf{q} : the message is appended to the session queue and the operation reduces to **return** (). The E-REACT rule captures the event-driven nature of the system: if an actor is idle with state V , and has a stored handler for $s[\mathbf{p}]$, and there exists a matching message in the session queue, then the message is dequeued and the message handler is evaluated with the message payload and state. If an actor is currently evaluating a computation in the context of a session $s[\mathbf{p}]$, rule E-SUSPEND evaluates **suspend** $V W$ by installing handler V for $s[\mathbf{p}]$ and returning the actor to the **idle**(W) state. Rule E-SPAWN spawns a fresh actor with empty handler and initialisation state, and E-RESET returns an actor to the **idle**(V) state once it has finished evaluating to an updated state V .

Session initialisation. Rule E-NEWAP creates an access point with a fresh name p and empty mappings for each role. Rule E-REGISTER evaluates **register** $p \mathbf{p} V$ by creating an initialisation token ι , storing a mapping from ι to the callback V in the requesting actor's initialisation state, and appending ι to the participant set for \mathbf{p} in p . Finally, E-INIT establishes a session when idle participants are registered for all roles: the rule discards all initialisation tokens, creates a session name restriction and empty session queue, and invokes all initialisation callbacks.

Example 3.1. Consider a simple Ping-Pong example. We can describe the protocol as:

$$\text{PingPong} = \left\{ \begin{array}{l} \text{Pinger} : \text{Ponger} \oplus \text{Ping}(\text{Unit}) . \text{Ponger} \& \text{Pong}(\text{Unit}) . \text{end}, \\ \text{Ponger} : \text{Pinger} \& \text{Ping}(\text{Unit}) . \text{Pinger} \oplus \text{Pong}(\text{Unit}) . \text{end} \end{array} \right\}$$

Configuration reduction

$$\boxed{C \xrightarrow{l} \mathcal{D}}$$

<p>E-SEND</p> $\frac{\langle a, (\mathcal{E}[\mathbf{q}! \ell(V)])^{s[p]}, \sigma, \rho \rangle \parallel s \triangleright \delta \xrightarrow{s}}{\langle a, (\mathcal{E}[\mathbf{return} ()])^{s[p]}, \sigma, \rho \rangle \parallel s \triangleright \delta \cdot (\mathbf{p}, \mathbf{q}, \ell(V))}$	<p>E-REACT</p> $\frac{(\ell(x) \mapsto M) \in \vec{H}}{\langle a, \mathbf{idle}(W), \sigma[s[p] \mapsto \mathbf{handler} \mathbf{q} \text{ st } \{\vec{H}\}], \rho \rangle \parallel s \triangleright (\mathbf{q}, \mathbf{p}, \ell(V)) \cdot \delta \xrightarrow{s} \langle a, (M\{V/x, W/st\})^{s[p]}, \sigma, \rho \rangle \parallel s \triangleright \delta}$	
<p>E-SUSPEND</p> $\frac{\langle a, (\mathcal{E}[\mathbf{suspend} V W])^{s[p]}, \sigma, \rho \rangle \xrightarrow{\tau}}{\langle a, \mathbf{idle}(W), \sigma[s[p] \mapsto V], \rho \rangle}$	<p>E-SPAWN</p> $\frac{\langle a, M[\mathbf{spawn} M], \sigma, \rho \rangle \xrightarrow{\tau}}{(vb)(\langle a, M[\mathbf{return} ()], \sigma, \rho \rangle \parallel \langle b, M, \epsilon, \epsilon \rangle)}$	<p>E-RESET</p> $\frac{\langle a, Q[\mathbf{return} V], \sigma, \rho \rangle \xrightarrow{\tau}}{\langle a, \mathbf{idle}(V), \sigma, \rho \rangle}$
<p>E-NEWAP</p> $\frac{p \text{ fresh}}{\langle a, M[\mathbf{newAP}[(p_i : S_i)_{i \in I}]], \sigma, \rho \rangle \xrightarrow{\tau} (vp)(\langle a, M[\mathbf{return} p], \sigma, \rho \rangle \parallel p((p_i \mapsto \emptyset)_{i \in I}))}$	<p>E-REGISTER</p> $\frac{t \text{ fresh}}{\langle a, M[\mathbf{register} p \mathbf{p} V], \sigma, \rho \rangle \parallel p(\chi[p \mapsto \tilde{t}']) \xrightarrow{\tau} (vt)(\langle a, M[\mathbf{return} ()], \sigma, \rho[t \mapsto V] \rangle \parallel p(\chi[p \mapsto \tilde{t}' \cup \{t\}]))}$	
<p>E-INIT</p> $\frac{s \text{ fresh}}{(v\iota_{p_i})_{i \in 1..n} (p((p_i \mapsto \tilde{t}'_{p_i} \cup \{t_{p_i}\})_{i \in 1..n}) \parallel \langle a_i, \mathbf{idle}(W_i), \sigma_i, \rho_i[t_{p_i} \mapsto V_i] \rangle_{i \in 1..n}) \xrightarrow{\tau} (vs)(p((p_i \mapsto \tilde{t}'_{p_i})_{i \in 1..n}) \parallel s \triangleright \epsilon \parallel \langle a_i, (V_i W_i)^{s[p_i]}, \sigma_i, \rho_i \rangle_{i \in 1..n})}$		<p>E-PAR</p> $\frac{C \xrightarrow{l} C'}{C \parallel \mathcal{D} \xrightarrow{l} C' \parallel \mathcal{D}}$
<p>E-LIFT</p> $\frac{M \longrightarrow_M N}{\langle a, M[M], \sigma, \rho \rangle \xrightarrow{\tau} \langle a, M[N], \sigma, \rho \rangle}$	<p>E-NU</p> $\frac{C \xrightarrow{l} \mathcal{D}}{(v\alpha)C \xrightarrow{l-\alpha} (v\alpha)\mathcal{D}}$	<p>E-STRUCT</p> $\frac{C \equiv C' \quad C' \xrightarrow{l} \mathcal{D}' \quad \mathcal{D}' \equiv \mathcal{D}}{C \xrightarrow{l} \mathcal{D}}$

where $l - \alpha = \tau$ if $l = \alpha$, and l otherwise

Fig. 11. Operational semantics (2)

We will abbreviate **Pinger** as **Pi** and **Ponger** as **Po**. The main function and the initialisation functions for the Pinger and Ponger are described as:

$\mathbf{main} \triangleq \mathbf{let} \mathbf{ap} = \mathbf{newAP}[\mathbf{PingPong}] \mathbf{in} \mathbf{spawn} \mathbf{pinger} \mathbf{ap}; \mathbf{spawn} \mathbf{ponger} \mathbf{ap}$

$\mathbf{ponger} \triangleq \lambda \mathbf{ap}. \mathbf{register} \mathbf{ap} \mathbf{Po} \mathbf{pongerCallback}$
 $\mathbf{pongerCallback} \triangleq \lambda().$
 $\mathbf{suspend} (\mathbf{handler} \mathbf{Pi} \text{ st } \{\mathbf{Ping} \mapsto \mathbf{Pi}! \mathbf{Pong}(\cdot)\}) ()$

$\mathbf{pinger} \triangleq \lambda \mathbf{ap}. \mathbf{register} \mathbf{ap} \mathbf{Pi} \mathbf{pingerCallback}$
 $\mathbf{pingerCallback} \triangleq \lambda().$
 $\mathbf{Po}! \mathbf{Ping}(\cdot);$
 $\mathbf{suspend} (\mathbf{handler} \mathbf{Po} \text{ st } \{\mathbf{Pong} \mapsto (\cdot)\}) ()$

With these defined, we place the main function in an initial configuration, which creates a new access point p (E-NEWAP) and spawns the Pinger and Ponger actors (E-SPAWN):

$$(va)(\langle a, \mathbf{main}, \epsilon, \epsilon \rangle) \longrightarrow^+ (vping)(vpong)(vp)(va) \left(\langle a, \mathbf{idle}(\cdot), \epsilon, \epsilon \rangle \parallel \langle ping, \mathbf{pinger}, \epsilon, \epsilon \rangle \parallel \langle pong, \mathbf{ponger}, \epsilon, \epsilon \rangle \parallel p(\mathbf{Pi} \mapsto \emptyset, \mathbf{Po} \mapsto \emptyset) \right)$$

At this point, both of the actors can register with the access point (E-REGISTER). By registering, the access points generate *initialisation tokens* t_1, t_2 , which are stored both in the access point and also as keys in the actors' initialisation states. The actors then revert to being idle (E-RESET).

$$\longrightarrow^+ (vt_1)(vt_2)(vping)(vpong)(vp)(va) \left(\langle a, \mathbf{idle}(\cdot), \epsilon, \epsilon \rangle \parallel \langle ping, \mathbf{idle}(\cdot), \epsilon, t_1 \mapsto \mathbf{pingerCallback} \rangle \parallel \langle pong, \mathbf{idle}(\cdot), \epsilon, t_2 \mapsto \mathbf{pongerCallback} \rangle \parallel p(\mathbf{Pi} \mapsto \{t_1\}, \mathbf{Po} \mapsto \{t_2\}) \right)$$

Since the access point now has idle registered actors for each role, it establishes a session and removes the initialisation tokens (E-INIT). Both actors evaluate their initialisation callbacks in the context of the newly-created session:

$$\longrightarrow^+ (vs)(vping)(vpong)(vp)(va) \left(\langle a, \mathbf{idle}(\cdot), \epsilon, \epsilon \rangle \parallel \langle ping, (\mathbf{pingerCallback}())^{s[\mathbf{Pi}]}, \epsilon, \epsilon \rangle \parallel \langle pong, (\mathbf{pongerCallback}())^{s[\mathbf{Po}]}, \epsilon, \epsilon \rangle \parallel p(\mathbf{Pi} \mapsto \emptyset, \mathbf{Po} \mapsto \emptyset) \parallel s \triangleright \epsilon \right)$$

Runtime types, environments, and labels

Polarised initialisation tokens	$t^\pm ::= t^+ \mid t^-$
Queue types	$Q ::= \epsilon \mid (p, q, \ell(A)) \cdot Q$
Runtime type environments	$\Delta ::= \cdot \mid \Delta, a \mid \Delta, p \mid \Delta, t^\pm : S \mid \Delta, s[p] : S \mid \Delta, s : Q$
Labels	$\gamma ::= s : p \uparrow q :: \ell \mid s : p \downarrow q :: \ell \mid \text{end}(s, p)$

Structural congruence (queue types)

$$Q \equiv Q'$$

$$\frac{p_1 \neq p_2 \vee q_1 \neq q_2}{Q_1 \cdot (p_1, q_1, \ell_1(A_1)) \cdot (p_2, q_2, \ell_2(A_2)) \cdot Q_2 \equiv Q_1 \cdot (p_2, q_2, \ell_2(A_2)) \cdot (p_1, q_1, \ell_1(A_1)) \cdot Q_2}$$

Runtime type environment reduction

$$\Delta \xrightarrow{\gamma} \Delta'$$

LBL-SEND	$\Delta, s[p] : \mathbf{q} \oplus \{\ell_i(A_i).S_i\}_{i \in I}, s : Q \xrightarrow{s:p \uparrow q :: \ell_j} \Delta, s[p] : S_j, s : Q \cdot (p, q, \ell_j(A_j)) \quad (j \in I)$
LBL-RECV	$\Delta, s[p] : \mathbf{q} \& \{\ell_i(A_i).S_i\}_{i \in I}, s : (q, p, \ell_j(A_j)) \cdot Q \xrightarrow{s:q \downarrow p :: \ell_j} \Delta, s[p] : S_j, s : Q \quad (\text{if } j \in I)$
LBL-END	$\Delta, s[p] : \text{end} \xrightarrow{\text{end}(s,p)} \Delta$
LBL-REC	$\Delta, s[p] : \mu X.S \xrightarrow{Y} \Delta' \quad (\text{if } \Delta, s[p] : S\{\mu X.S/X\} \xrightarrow{Y} \Delta')$

Fig. 12. Labelled transition system on runtime type environments

Following the behaviour in the callbacks, the Ponger suspends awaiting a message (E-SUSPEND), and the Pinger sends a message to the Ponger, which is stored in the session queue (E-SEND).

$$\longrightarrow^+ (vs)(vping)(vpong)(vp)(va) \left(\begin{array}{l} \langle a, \text{idle}(), \epsilon, \epsilon \rangle \parallel \langle ping, (\text{suspend}(\text{handler } \mathbf{Po} \text{ st } \{\text{Pong} \mapsto ()\})()) \rangle^{s[\mathbf{Pi}]} \langle \epsilon, \epsilon \rangle \\ \parallel \langle pong, \text{idle}(), s[\mathbf{Po}] \mapsto \text{handler } \mathbf{Pi} \text{ st } \{\text{Ping} \mapsto \mathbf{Pi}! \text{Pong}()\}, \epsilon \rangle \\ \parallel p(\mathbf{Pi} \mapsto \emptyset, \mathbf{Po} \mapsto \emptyset) \parallel s \triangleright (\mathbf{Pi}, \mathbf{Po}, \text{Ping}()) \end{array} \right)$$

The Pinger can now suspend, awaiting a message from the Ponger (E-SUSPEND). Since there is a queued message for the idle Ponger, we can re-activate the suspended handler (E-REACT):

$$\longrightarrow^+ (vs)(vping)(vpong)(vp)(va) \left(\begin{array}{l} \langle a, \text{idle}(), \epsilon, \epsilon \rangle \\ \parallel \langle ping, \text{idle}(), s[\mathbf{Pi}] \mapsto \text{handler } \mathbf{Po} \text{ st } \{\text{Pong} \mapsto ()\}, \epsilon \rangle \\ \parallel \langle pong, (\mathbf{Pi}! \text{Pong}()) \rangle^{s[\mathbf{Po}]} \langle \epsilon, \epsilon \rangle \\ \parallel p(\mathbf{Pi} \mapsto \emptyset, \mathbf{Po} \mapsto \emptyset) \parallel s \triangleright \epsilon \end{array} \right)$$

Finally, the Ponger can send a Pong back to the Pinger, which activates the stored handler:

$$\longrightarrow^+ (vs)(vping)(vpong)(vp)(va) \left(\begin{array}{l} \langle a, \text{idle}(), \epsilon, \epsilon \rangle \parallel \langle ping, () \rangle^{s[\mathbf{Pi}]} \langle \epsilon, \epsilon \rangle \parallel \langle pong, () \rangle^{s[\mathbf{Po}]} \langle \epsilon, \epsilon \rangle \\ \parallel p(\mathbf{Pi} \mapsto \emptyset, \mathbf{Po} \mapsto \emptyset) \parallel s \triangleright \epsilon \end{array} \right)$$

Both actors have now finished the session and therefore revert to being idle (E-RESET).

4 Metatheory

In order to prove properties about Maty, we define an extrinsic [52] type system for Maty configurations. This is only used for our proofs; we do not need to implement it in a typechecker.

Following Scalas and Yoshida [55] we begin by showing a type semantics for sets of local types. Using this semantics we can ensure that collections of local types are *compliant*, meaning that communicated messages are always compatible and that communication is deadlock-free, and use this to prove type preservation, progress, and global progress for Maty configurations.

Relations. We write $\mathcal{R}^?$, \mathcal{R}^+ , and \mathcal{R}^* for the reflexive, transitive, and reflexive-transitive closures of a relation \mathcal{R} respectively. We write $\mathcal{R}_1 \mathcal{R}_2$ for the composition of relations \mathcal{R}_1 and \mathcal{R}_2 .

Runtime types and environments. Runtime environments are used to type configurations and to define behavioural properties on sets of local types. Unlike type environments Γ , runtime type environments Δ are *linear* to ensure safe use of session endpoints, and also to ensure that there is precisely one instance of each actor and access point. Runtime type environments can contain actor names a ; access point names p ; *polarised* initialisation tokens $t^\pm : S$ (since each initialisation

token is used twice: once in the access point and one inside an actor's initialisation state); session endpoints $s[\mathbf{p}] : S$; and finally session queue types $s : Q$. Queue types mirror the structure of queue entries and consist of a series of triples $(\mathbf{p}, \mathbf{q}, \ell(A))$. We include structural congruence on queue types to match structural congruence on queues, and extend this to runtime environments.

Labelled transition system on environments. Figure 12 shows the LTS on runtime type environments. The LBL-SEND reduction gives the behaviour of an output session type interacting with a queue: supposing we send a message with some label ℓ_j from \mathbf{p} to \mathbf{q} , we advance the session type for \mathbf{p} to the continuation S_j and add the message to the end of the queue. The LBL-RECV rule handles receiving and works similarly, instead *consuming* the message from the queue. Rule LBL-END allows us to discard a session endpoint from the environment if it does not support any further communication, and LBL-REC allows reduction of recursive session types by considering their unrolling. We write $\Delta \Longrightarrow \Delta'$ if $\Delta \xrightarrow{\gamma} \equiv \Delta'$ for some synchronisation label γ , and conversely write $\Delta \not\Longrightarrow$ if there exists no Δ' such that $\Delta \Longrightarrow \Delta'$.

Protocol Properties. In order to prove type preservation and progress properties on Maty configurations, we need to ensure each protocol in the system is *compliant*, meaning that it is safe and deadlock-free. *Safety* is the minimum we can expect from a protocol in order for us to prove type preservation: a safe runtime type environment ensures that communication does not introduce type errors. Intuitively, safety ensures that a message received from a queue is of the expected type, thereby ruling out communication mismatches; safety properties must also hold under unfoldings of recursive session types and safety must be preserved by environment reduction. Deadlock-freedom on runtime type environments requires that every message that is sent in a protocol can eventually be received, and that a participant will never wait for a message that will never arrive.

Definition 4.1 (Compliance). A runtime environment Δ is *compliant*, written $\text{comp}(\Delta)$, if it is *safe* and *deadlock-free*:

Safe An environment Δ is *safe*, written $\text{safe}(\Delta)$, if:

- $\Delta = \Delta', s[\mathbf{p}] : \mathbf{q} \& \{\ell_i(A_i).S_i\}_{i \in I}, s : Q$ with $Q \equiv (\mathbf{q}, \mathbf{p}, \ell_j(B_j)) \cdot Q'$ implies $j \in I$ and $B_j = A_j$; and
- $\Delta = \Delta', s[\mathbf{p}] : \mu X.S$ implies $\text{safe}(\Delta', s[\mathbf{p}] : S\{\mu X.S/X\})$; and
- $\text{safe}(\Delta)$ and $\Delta \Longrightarrow \Delta'$ implies $\text{safe}(\Delta')$.

Deadlock-free An environment Δ is *deadlock-free*, written $\text{df}(\Delta)$, if $\Delta \Longrightarrow^* \Delta' \not\Longrightarrow$ implies $\Delta' = s : \epsilon$.

A *protocol* $\{\mathbf{p}_i : S_i\}_{i \in 1..n}$ is compliant if $\text{comp}(s[\mathbf{p}_1] : S_1, \dots, s[\mathbf{p}_n] : S_n)$ for an arbitrary s .

Checking compliance for an *asynchronous* protocol is undecidable in general [55], but various sound and tractable mechanisms can ensure it in practice. For example, syntactic projections from global types produce safe and deadlock-free sets of local types [55]. Furthermore, multiparty compatibility [19] allows safety to be verified by bounded model checking; this is the core approach implemented in Scribble [36], used by our implementation.

We have therefore designed our type system to be agnostic to any specific implementation method for validating compliance, as common in recent MPST language design papers (e.g., [30, 40]).

4.1 Configuration Typing

Figure 13 shows the typing rules for Maty configurations. The configuration typing judgement $\Gamma; \Delta \vdash C$ can be read, “under type environment Γ and runtime type environment Δ , configuration C is well typed”. We have three rules for name restrictions: read bottom-up, T-APNAME adds p to both environments, and rule T-INITNAME adds tokens of both polarities to the runtime type environment. Rule T-SESSIONNAME is key to the generalised multiparty session typing approach introduced by Scalas and Yoshida [55]: to type a name restriction $(\nu s)C$, the type environment Δ' consists of a

Configuration typing rules

$$\begin{array}{c}
\boxed{\Gamma; \Delta \vdash C} \\
\text{T-SESSIONNAME} \\
\frac{\Delta' = \{s[\mathbf{p}_i] : S_{\mathbf{p}_i}\}_{i \in 1..n}, s : Q}{\text{comp}(\Delta')} \\
\frac{s \notin \text{snames}(\Delta) \quad \Gamma; \Delta, \Delta' \vdash C}{\Gamma; \Delta \vdash (vs)C} \\
\text{T-APNAME} \quad \frac{\Gamma, p : \text{AP}(\{(p_i : S_i)_{i \in I}\}; \Delta, p \vdash C)}{\Gamma; \Delta \vdash (vp)C} \quad \text{T-INITNAME} \quad \frac{\Gamma; \Delta, t^+ : S, t^- : S \vdash C}{\Gamma; \Delta \vdash (vi)C} \quad \text{T-ACTORNAME} \quad \frac{\Gamma; \Delta, a \vdash C}{\Gamma; \Delta \vdash (va)C} \\
\text{T-PAR} \quad \frac{\Gamma; \Delta_1 \vdash C \quad \Gamma; \Delta_2 \vdash D}{\Gamma; \Delta_1, \Delta_2 \vdash C \parallel D} \quad \text{T-AP} \quad \frac{p : \text{AP}(\{(p_i : S_i)_{i \in I}\}) \in \Gamma \quad \{\{p_i : S_i\}_{i \in I}\} \Delta \vdash \chi \quad \text{comp}(\{\{p_i : S_i\}_{i \in I}\})}{\Gamma; \Delta, p \vdash p(\chi)} \quad \text{T-ACTOR} \quad \frac{\Gamma; \Delta_1 \mid A \vdash \mathcal{T} \quad \Gamma; \Delta_2 \mid A \vdash \sigma \quad \Gamma; \Delta_3 \mid A \vdash \rho}{\Gamma; \Delta_1, \Delta_2, \Delta_3, a \vdash \langle a, \mathcal{T}, \sigma, \rho \rangle} \\
\text{T-EMPTYQUEUE} \quad \frac{}{\Gamma; s : \epsilon \vdash s \triangleright \epsilon} \quad \text{T-CONSQUEUE} \quad \frac{\Gamma \vdash V : A \quad \Gamma; s : Q \vdash s \triangleright \sigma}{\Gamma; s : ((p, q, \ell(A)) \cdot Q) \vdash s \triangleright (p, q, \ell(V)) \cdot \sigma}
\end{array}$$

Access point typing

$$\boxed{\{(p_i : S_i)_i\} \Delta \vdash \chi} \\
\text{TA-EMPTY} \quad \frac{}{\{(p_i : S_i)_{i \in 1..n}\} \cdot \vdash \cdot}$$

$$\text{TA-ENTRY} \quad \frac{j \in I \quad \{(p_i : S_i)_{i \in I}\} \Delta \vdash \chi}{\{(p_i : S_i)_{i \in I}\} \Delta, t^- : S_j \vdash \chi[p_j \mapsto \bar{t}]}$$

Thread state typing

$$\boxed{\Gamma; \Delta \mid A \vdash \mathcal{T}} \\
\text{TT-IDLE} \quad \frac{\Gamma \vdash V : A}{\Gamma; \cdot \mid A \vdash \text{idle}(V)}$$

$$\text{TT-SESS} \quad \frac{\Gamma \mid A \mid S \triangleright M : A \triangleleft \text{end}}{\Gamma; s[\mathbf{p}] : S \mid A \vdash (M)^{s[\mathbf{p}]}} \quad \text{TT-NOSESS} \quad \frac{\Gamma \mid A \mid \text{end} \triangleright M : A \triangleleft \text{end}}{\Gamma; \cdot \mid A \vdash M}$$

Handler state typing

$$\boxed{\Gamma; \Delta \mid A \vdash \sigma} \\
\text{TH-EMPTY} \quad \frac{}{\Gamma; \cdot \mid A \vdash \epsilon} \quad \text{TH-HANDLER} \quad \frac{\Gamma \vdash V : \text{Handler}(S^2, A) \quad \Gamma; \Delta \mid A \vdash \sigma}{\Gamma; \Delta, s[\mathbf{p}] : S^2 \mid A \vdash \sigma[s[\mathbf{p}] \mapsto V]}$$

Initialisation state typing

$$\boxed{\Gamma; \Delta \mid A \vdash \rho} \\
\text{TI-EMPTY} \quad \frac{}{\Gamma; \cdot \mid A \vdash \epsilon} \quad \text{TI-CALLBACK} \quad \frac{\Gamma \vdash V : A \xrightarrow{S, \text{end}} A \quad \Gamma; \Delta \mid A \vdash \rho}{\Gamma; \Delta, t^+ : S \mid A \vdash \rho[t \mapsto V]}$$

$$\text{snames}(\Delta) = \{s \mid s : Q \in \Delta \vee \exists \mathbf{p}. (s[\mathbf{p}] \in \text{dom}(\Delta))\}$$

Fig. 13. Typing of Configurations

set of session endpoints $\{s[\mathbf{p}_i]\}_i$ with session types $S_{\mathbf{p}_i}$, along with a session queue $s : Q$. We call Δ' the *session environment for s* , which must be compliant. The condition $s \notin \text{snames}(\Delta)$ ensures that no other endpoint or queue with session name s may be present in the initial environment.

Rule T-PAR types two parallel subconfigurations under disjoint runtime environments. Rule T-AP types an access point: it requires that the access point reference is included in Γ and through the auxiliary judgement $\{(p_i : S_i)_i\} \Delta \vdash \chi$ ensures that each initialisation token in the access point has a compatible type. We also require that the protocol supported by the access point is compliant.

Rule T-ACTOR types an actor $\langle a, \mathcal{T}, \sigma, \rho \rangle$ using three auxiliary judgements. The thread state typing judgement $\Gamma; \Delta \mid C \vdash \mathcal{T}$ ensures that a thread either performs all pending communication actions, or it suspends. The handler typing judgement $\Gamma; \Delta \mid C \vdash \sigma$ ensures that the stored handlers match the types in the runtime environments, and the initialisation state typing judgement $\Gamma; \Delta \mid C \vdash \rho$ ensures that all initialisation callbacks match the session type of the initialisation token. Finally, T-EMPTYQUEUE and T-CONSQUEUE ensure that queued messages match the queue type.

4.2 Properties

With configuration typing defined, we can begin to describe the properties enjoyed by Maty.

4.2.1 Preservation. Typing is preserved by reduction; consequently we know that communication actions must match those specified by the session type. Proofs can be found in the extended version.

THEOREM 4.2 (PRESERVATION). *Typability is preserved by structural congruence and reduction.*

(\equiv) If $\Gamma; \Delta \vdash C$ and $C \equiv \mathcal{D}$ then there exists some $\Delta' \equiv \Delta$ such that $\Gamma; \Delta' \vdash \mathcal{D}$.

(\rightarrow) If $\Gamma; \Delta \vdash C$ with $\text{safe}(\Delta)$ and $C \rightarrow \mathcal{D}$, then there exists some Δ' such that $\Delta \Longrightarrow^? \Delta'$ where $\text{safe}(\Delta')$ and $\Gamma; \Delta' \vdash \mathcal{D}$.

Remark 4.3 (Session Fidelity). Traditionally, *session fidelity* is presented as a property that all communication in a system conforms to its associated session type, i.e., that if a process performs a communication action then there is a corresponding (meta-theoretical) type reduction [15, 32]. Fidelity is often an implicit corollary of type preservation in works on functional session types (e.g., [25, 28, 30, 43]). Alternatively, session fidelity in [55] (and derived works) refer to session fidelity as the property that at least one typing context reduction can be reflected by a process. We follow the former definition and account for fidelity through our preservation theorem.

4.2.2 Progress. In general, just because two protocols are individually deadlock-free *does not* mean that the system as a whole is deadlock-free, due to the possibility of inter-session deadlocks. For example, consider the following two trivially deadlock-free protocols:

$$\{p : q \& \{\ell_1(\text{Unit}) . \text{end}\}, q : p \oplus \{\ell_1(\text{Unit}) . \text{end}\}\} \quad \{r : s \& \{\ell_2(\text{Unit}) . \text{end}\}, s : r \oplus \{\ell_2(\text{Unit}) . \text{end}\}\}$$

Even with an asynchronous semantics, a standard multiparty process calculus would admit the following deadlocking process, since each send is blocked by a receive:

$$s_1[p][q] \& \ell_1(x) . s_2[r][s] \oplus \ell_2(y) . 0 \parallel s_2[s][r] \& \ell_2(a) . s_1[q][p] \oplus \ell_1(b) . 0$$

There are various approaches to ruling out inter-session deadlocks: some approaches restrict each subprocess to only play a single role in a single session (e.g., [55]); this would rule out the above example but is too restrictive for our setting. Other approaches (e.g., [15]) overlay additional interaction type systems to rule out inter-process deadlocks, again at the cost of expressiveness and type system complexity. Finally, logically-inspired approaches to multiparty session typing (e.g., [9]) treat sessions as monolithic processes ($(\nu s)(P_1 \parallel \dots \parallel P_n)$) that mean that such cycles cannot arise. Programming with such processes requires “multi-fork” style session initiations that combine channel- and process creation, and therefore are inapplicable to our programming model.

Maty *does not* suffer from inter-process deadlocks because of our event-driven programming style where although an actor is involved in many sessions at a time, only one is *running* at once, and code within handlers does not block. Since an actor yields and installs a handler whenever it needs to receive a message, the actor can then schedule any handler that has a waiting message.

To show this intuition formally, we start by classifying a *canonical form* for configurations.

Definition 4.4 (Canonical form). A configuration C is in *canonical form* if it can be written:

$$(\tilde{\nu} i)(\nu p_{i \in 1..l})(\nu s_{j \in 1..m})(\nu a_{k \in 1..n})(p_i(\chi_i)_{i \in 1..l} \parallel (s_j \triangleright \delta_j)_{j \in 1..m} \parallel \langle a_k, \mathcal{T}_k, \sigma_k, \rho_k \rangle_{k \in 1..n})$$

Every well typed configuration can be written in canonical form; the result follows from the structural congruence rules and Theorem 4.2.

Compliance requires the session *types* in every session to satisfy progress. Due to our event-driven design, the property transfers to *configurations*: a non-reducing closed configuration cannot be blocked on any session communication and so cannot contain any sessions.

Progress states that since (by compliance) all protocols are deadlock-free, a configuration can either reduce, or it contains no sessions and no further sessions can be established.

THEOREM 4.5 (PROGRESS). *If $\cdot; \vdash C$, then either there exists some \mathcal{D} such that $C \longrightarrow \mathcal{D}$, or C is structurally congruent to the following canonical form:*

$$(\tilde{\nu} i)(\nu p_{i \in 1..m})(\nu a_{j \in 1..n})(p_1(\chi_1)_{i \in 1..m} \parallel \langle a_j, \text{idle}(V_j), \epsilon, \rho_j \rangle_{j \in 1..n})$$

4.2.3 Global Progress. *Global progress* extends Theorem 4.5 to show that if all event handlers terminate (a usual assumption in event-driven systems), then communication is eventually possible

for any session with pending communication actions. The technical development shows that thread reduction in one actor does not block another (Lemma 4.9); that if all threads terminate, the configuration can reach an idle state (Corollary 4.11); and that from any idle configuration, we can invoke a handler for any session with pending communication actions (Lemma 4.12).

We begin by defining configuration contexts $\mathcal{G} ::= [] \mid (\nu\alpha)\mathcal{G} \mid \mathcal{G} \parallel C \mid C \parallel \mathcal{G}$ that allow us to focus on a subconfiguration. We say that $\langle a, M, \sigma, \rho \rangle$ is an *actor subconfiguration* of a configuration C if $C = \mathcal{G}[\langle a, M, \sigma, \rho \rangle]$ for some configuration context \mathcal{G} .

Definition 4.6 (Ongoing environment / session). We say that a runtime type environment Δ is *ongoing*, written $\text{ongoing}(\Delta)$, if it contains at least one entry of the form $s[\mathbf{p}] : S$ where $S \neq \text{end}$. A *session* is ongoing if its session environment is ongoing.

Given a derivation $\Gamma; \Delta \vdash C$ we can annotate each name restriction $(\nu s)\mathcal{D}$ appearing in C with its session environment (i.e., to $(\nu s : \Delta')\mathcal{D}$ if session s has session environment Δ'). We define $\text{ongoingSessions}(C)$ as the set of session names in C with ongoing session environments, with the remaining cases defined recursively:

$$\text{ongoingSessions}((\nu s : \Delta)C) = \begin{cases} \{s\} \cup \text{ongoingSessions}(C) & \text{if } \text{ongoing}(\Delta) \\ \text{ongoingSessions}(C) & \text{otherwise} \end{cases}$$

We now classify *thread-terminating* actors: an actor is thread-terminating if it will eventually either suspend with a handler or fully evaluate to a value. A *thread reduction* for an actor a is a configuration reduction that affects the ongoing thread of a .

Definition 4.7 (Thread Reduction). A reduction $C \longrightarrow \mathcal{D}$ where $C = \mathcal{G}_1[\langle a, \mathcal{M}[M], \sigma, \rho \rangle]$ and $\mathcal{D} = \mathcal{G}_2[\langle a, \mathcal{M}[N], \sigma', \rho' \rangle]$ is a *thread reduction for a* if $\langle a, \mathcal{M}[M], \sigma, \rho \rangle$ is a subconfiguration of the fired redex of C , and $\langle a, \mathcal{M}[N], \sigma', \rho' \rangle$ is a subconfiguration of its contractum.

Definition 4.8 (Thread-Terminating). An actor subconfiguration $\langle a, \mathcal{T}, \sigma, \rho \rangle$ of a configuration $C = \mathcal{G}[\langle a, \mathcal{T}, \sigma, \rho \rangle]$ is *thread-terminating* if either $\mathcal{T} = \mathbf{idle}(V)$ for some V , or $\mathcal{T} = \mathcal{M}[M]$ such that there exists no infinite thread reduction for a from C .

We deliberately design our metatheory to be agnostic to the precise method used to ensure termination. Concretely, to ensure that actors are always thread-terminating, we could for example use straightforward type system restrictions like requiring all callbacks and handlers to be total or use primitive recursion. We could also use effect-based analyses (e.g. those used for ensuring safe database programming [42]). We conjecture we could also adapt type systems designed to enforce *fair termination* [14, 51]; we discuss this further in Section 7. The additional power of exceptions described in Section 5 would also allow the smooth integration of run-time termination analyses. All of the example callbacks and handlers discussed in the paper would preserve thread-termination.

Next, we show that reduction in one actor will never inhibit reduction in another. The result follows because all communication is asynchronous and (in part due to Theorem 4.5), given a well-typed configuration, all constructs occurring in an actor's thread can always reduce immediately.

LEMMA 4.9 (INDEPENDENCE OF THREAD REDUCTIONS). *If $\cdot; \vdash C$ where $C = \mathcal{G}_1[\langle a, \mathcal{M}[M], \sigma, \rho \rangle]$ and $C \longrightarrow \mathcal{G}_2[\langle a, \mathcal{M}[N], \sigma', \rho' \rangle]$ is a thread reduction for a , then for every \mathcal{D} and \mathcal{G}_3 such that $C \longrightarrow \mathcal{D}$ and $\mathcal{D} = \mathcal{G}_3[\langle a, \mathcal{M}[M], \sigma, \rho \rangle]$ it follows that $\mathcal{D} \longrightarrow \mathcal{G}_4[\langle a, \mathcal{M}[N], \sigma', \rho' \rangle]$ for some \mathcal{G}_4 .*

Definition 4.10 (Idle Configuration). An actor subconfiguration $\langle a, \mathcal{T}, \sigma, \rho \rangle$ of a configuration C is *idle* if $\mathcal{T} = \mathbf{idle}(V)$ for some V . Configuration C is *idle* if all of its actor subconfigurations are idle.

It follows by typing and from Lemma 4.9 that every thread-terminating actor subconfiguration of a configuration C eventually evaluates to either **return** V or **suspend** V W and that (via E-SUSPEND or E-RETURN) C reverts to being idle.

Syntax

Types	$A, B ::= \dots \mid \text{Pid}$	Monitored processes	$\omega ::= \overline{(a, V)}$
Values	$V, W ::= \dots \mid a$	Configurations	$C, \mathcal{D} ::= \dots \mid \langle a, \mathcal{T}, \sigma, \rho, \omega \rangle$
Computations	$M, N ::= \dots \mid \mathbf{suspend} \ U \ V \ W$ $\mid \mathbf{monitor} \ V \ W \mid \mathbf{raise}$		$\mid \not\downarrow a \mid \not\downarrow s[p] \mid \not\downarrow t$

Modified typing rules for computations

$$\boxed{\Gamma \mid C \mid S \triangleright M : A \triangleleft T}$$

$\frac{\text{T-SPAWN} \quad \Gamma \mid A \mid \text{end} \triangleright M : A \triangleleft \text{end}}{\Gamma \mid C \mid S \triangleright \mathbf{spawn} \ M : \text{Pid} \triangleleft S}$	$\frac{\text{T-SUSPEND} \quad \Gamma \vdash U : \text{Handler}(S^2, C) \quad \Gamma \vdash V : C \quad \Gamma \vdash W : C \xrightarrow{\text{end, end}} C}{\Gamma \mid C \mid S^2 \triangleright \mathbf{suspend} \ U \ V \ W : A \triangleleft T}$
$\frac{\text{T-MONITOR} \quad \Gamma \vdash V : \text{Pid} \quad \Gamma \vdash W : C \xrightarrow{\text{end, end}} C}{\Gamma \mid C \mid S \triangleright \mathbf{monitor} \ V \ W : \text{Unit} \triangleleft S}$	$\frac{\text{T-RAISE}}{\Gamma \mid C \mid S \triangleright \mathbf{raise} : A \triangleleft T}$

Modified configuration reduction rules

$$\boxed{C \xrightarrow{l} \mathcal{D}}$$

E-REACT	$\langle a, \mathbf{idle}(W), \sigma[s[p] \mapsto (\mathbf{handler} \ q \ st \ \{\vec{H}\}, U)], \rho, \omega \rangle \parallel s \triangleright (q, p, \ell(V)) \cdot \delta$ $\xrightarrow{s} \langle a, (M\{V/x, W/st\})^{s[p]}, \sigma, \rho, \omega \rangle \parallel s \triangleright \delta \quad \text{if } (\ell(V) \mapsto M) \in \vec{H}$
E-SPAWN	$\langle a, M[\mathbf{spawn} \ M], \sigma, \rho, \omega \rangle \xrightarrow{\tau} (vb)(\langle a, M[\mathbf{return} \ b], \sigma, \rho, \omega \rangle \parallel \langle b, M, \epsilon, \emptyset, \emptyset \rangle)$
E-SUSPEND	$\langle a, (\mathcal{E}[\mathbf{suspend} \ U \ V \ W])^{s[p]}, \sigma, \rho, \omega \rangle \xrightarrow{\tau} \langle a, \mathbf{idle}(V), \sigma[s[p] \mapsto (U, W)], \rho, \omega \rangle$
E-MONITOR	$\langle a, M[\mathbf{monitor} \ b \ V], \sigma, \rho, \omega \rangle \xrightarrow{\tau} \langle a, M[\mathbf{return} \ ()], \sigma, \rho, \omega \cup \{(b, V)\} \rangle$
E-INVOKEM	$\langle a, \mathbf{idle}(W), \sigma, \rho, \omega \cup \{(b, V)\} \rangle \parallel \not\downarrow b \xrightarrow{\tau} \langle a, (V \ W), \sigma, \rho, \omega \rangle \parallel \not\downarrow b$
E-RAISE	$\langle a, \mathcal{E}[\mathbf{raise}], \sigma, \rho, \omega \rangle \xrightarrow{\tau} \not\downarrow a \parallel \not\downarrow \sigma \parallel \not\downarrow \rho$
E-RAISES	$\langle a, (\mathcal{E}[\mathbf{raise}])^{s[p]}, \sigma, \rho, \omega \rangle \xrightarrow{\tau} \not\downarrow a \parallel \not\downarrow s[p] \parallel \not\downarrow \sigma \parallel \not\downarrow \rho$
E-CANCELMSG	$s \triangleright (p, q, \ell(V)) \cdot \delta \parallel \not\downarrow s[q] \xrightarrow{\tau} s \triangleright \delta \parallel \not\downarrow s[q]$
E-CANCELAP	$(v\iota)(p(\chi[p \mapsto \vec{t} \cup \{\iota\}]) \parallel \not\downarrow \iota) \xrightarrow{\tau} p(\chi[p \mapsto \vec{t}])$
E-CANCELH	$\langle a, \mathbf{idle}(W), \sigma[s[p] \mapsto (\mathbf{handler} \ q \ st \ \{\vec{H}\}, V)], \rho, \omega \rangle \parallel s \triangleright \delta \parallel \not\downarrow s[q]$ $\xrightarrow{\tau} \langle a, (V \ W), \sigma, \rho, \omega \rangle \parallel s \triangleright \delta \parallel \not\downarrow s[q] \parallel \not\downarrow s[p] \quad \text{if } \text{messages}(q, p, \delta) = \emptyset$ where $\text{messages}(p, q, \delta) = \{\ell(V) \mid (r, s, \ell(V)) \in \delta \wedge p = r \wedge q = s\}$

Structural congruence

$$\boxed{C \equiv \mathcal{D}}$$

Syntactic sugar

$(vs)(\not\downarrow s[p_i]_{i \in 1..n} \parallel s \triangleright \epsilon) \parallel C \equiv C$	$\not\downarrow \sigma \triangleq \not\downarrow s_1[p_1] \parallel \dots \parallel \not\downarrow s_n[p_n] \quad (\text{where } \text{dom}(\sigma) = \{s_i[p_i]\}_{i \in 1..n})$
$(va)(\not\downarrow a) \parallel C \equiv C$	$\not\downarrow \rho \triangleq \not\downarrow t_1 \parallel \dots \parallel \not\downarrow t_n \quad (\text{where } \text{dom}(\rho) = \{t_i\}_{i \in 1..n})$

Fig. 14. $\text{Maty}_{\not\downarrow}$: Modified syntax and reduction rules

COROLLARY 4.11. *If $\cdot; \vdash C$ and C is thread-terminating, then $C \xrightarrow{*} \mathcal{D}$ where \mathcal{D} is idle.*

Finally, due to session typing and compliance, every ongoing session in a well-typed idle configuration can reduce. The result is as a special case of Theorem 4.5.

LEMMA 4.12. *If $\cdot; \vdash C$ where C is idle, then for each $s \in \text{ongoingSessions}(C)$, $C \equiv (vs)\mathcal{D}$ and $\mathcal{D} \xrightarrow{s}$.*

Since (by Theorem 4.2) we can always use the structural congruence rules to hoist a session name restriction to the topmost level, global progress follows as an immediate corollary.

COROLLARY 4.13 (GLOBAL PROGRESS). *If $\cdot; \vdash C$ where C is thread-terminating, then for every $s \in \text{ongoingSessions}(C)$, $C \equiv (vs)\mathcal{D}$ for some \mathcal{D} , and $\mathcal{D} \xrightarrow{\tau} \xrightarrow{*} \xrightarrow{s}$.*

5 Failure Handling and Supervision

Actor languages support the *let-it-crash* philosophy, where actors fail fast and are restarted by supervisors. A crashed actor cannot send messages, so we need a mechanism to prevent sessions from getting stuck. We use the *affine sessions* approach [25, 30, 40, 46], where participants can

be marked as cancelled; receiving from a cancelled participant with an empty queue raises an exception, triggering a crash and propagating the failure. Figure 14 shows the additional syntax, typing rules, and reduction rules needed for supervision and cascading failure; we call this extension Maty_{ζ} . We make actors *addressable*, so **spawn** returns a process identifier (PID) of type Pid . The **monitor** $V W$ construct installs a callback function W to be evaluated should the actor referred to by V crash. The **raise** construct signifies a user-level error has occurred, for example **if**fileExists(*path*)**then**processFile(*path*)**else**raise. Like **suspend**, **raise** can be given an arbitrary type and post-condition since it does not return. We also modify **suspend** to take an additional callback to be run if the sender fails; a sensible piece of syntactic sugar is **suspend** $V W \triangleq$ **suspend** $V W (\lambda st. \text{raise})$ to propagate the failure.

We can make our shop actor robust by using a shopSup actor that restarts it upon failure:

$$\text{shopSup} \triangleq \lambda \text{custAP}. \mathbf{monitor} (\mathbf{spawn} \text{shop} (\text{custAP}, \text{initialStock})) (\text{shopSup} \text{custAP})$$

The shopSup actor spawns a shop actor and monitors the resulting PID. Any failure of the shop actor will be detected by the shopSup which will restart the actor and monitor it again. The restarted shop actor will re-register with the access points and can then take part in subsequent sessions.

Configurations. To capture the additional runtime behaviour we modify the actor configuration to $\langle a, \mathcal{T}, \sigma, \rho, \omega \rangle$, where ω pairs monitored PIDs with callbacks to be evaluated should the actor crash. We also introduce three kinds of “zapper thread”, ζa , $\zeta s[\mathbf{p}]$, $\zeta \iota$ to indicate the cancellation of an actor, role, and initialisation token respectively.

Reduction rules by example. Consider the supervised Shop example after the **Customer** has sent a Checkout request and is awaiting a response. Instead of suspending, **Shop** raises an exception. This scenario can be represented by the following configuration, where *shop*, *cust*, and *pp* are actors playing the **Shop**, **Customer**, and **PaymentProcessor** in session s , and *sup* is monitoring *shop*:

$$(vsup)(vshop)(vcust)(vpp)(vs) \left(\begin{array}{l} \langle \text{shop}, (\mathbf{raise})^{s[\mathbf{Shop}]}, \epsilon, \epsilon, \epsilon \rangle \\ \parallel \langle \text{cust}, \mathbf{idle}(), s[\mathbf{Customer}] \mapsto (\text{checkoutHandler}, \mathbf{raise}), \epsilon, \epsilon \rangle \\ \parallel \langle \text{pp}, \mathbf{idle}(), s[\mathbf{PaymentProcessor}] \mapsto (\text{buyHandler}, \mathbf{raise}), \epsilon, \epsilon \rangle \\ \parallel s \triangleright (\mathbf{Customer}, \mathbf{Shop}, \text{checkout}((\{123\}, 510))) \\ \parallel \langle \text{sup}, \mathbf{idle}(), \epsilon, \epsilon, (\text{shop}, \text{shopSup } cAP) \rangle \end{array} \right)$$

For brevity we shorten **Shop**, **Customer**, and **PaymentProcessor** to **S**, **C**, and **PP** respectively. We let context $\mathcal{G} = (vsup)(vshop)(vcust)(vpp)(vs)(\parallel \langle \text{sup}, \mathbf{idle}(), \epsilon, \epsilon, (\text{shop}, \text{shopSup } cAP) \rangle)$.

Since the *shop* actor is playing role $s[\mathbf{S}]$ and raising an exception, by E-RAISES the actor is replaced with zapper threads ζshop and $\zeta s[\mathbf{S}]$.

$$\mathcal{G} \left[\begin{array}{l} \langle \text{shop}, (\mathbf{raise})^{s[\mathbf{S}]}, \epsilon, \epsilon, \epsilon \rangle \\ \parallel \langle \text{cust}, \mathbf{idle}(), s[\mathbf{C}] \mapsto (\text{checkoutHandler}, \mathbf{raise}), \epsilon, \epsilon \rangle \\ \parallel \langle \text{pp}, \mathbf{idle}(), s[\mathbf{PP}] \mapsto (\text{buyHandler}, \mathbf{raise}), \epsilon, \epsilon \rangle \\ \parallel s \triangleright (\mathbf{C}, \mathbf{S}, \text{checkout}((\{123\}, 510))) \end{array} \right] \rightarrow \mathcal{G} \left[\begin{array}{l} \zeta \text{shop} \parallel \zeta s[\mathbf{S}] \\ \parallel \langle \text{cust}, \mathbf{idle}(), s[\mathbf{C}] \mapsto (\text{checkoutHandler}, \mathbf{raise}), \epsilon, \epsilon \rangle \\ \parallel \langle \text{pp}, \mathbf{idle}(), s[\mathbf{PP}] \mapsto (\text{buyHandler}, \mathbf{raise}), \epsilon, \epsilon \rangle \\ \parallel s \triangleright (\mathbf{C}, \mathbf{S}, \text{checkout}((\{123\}, 510))) \end{array} \right]$$

Next, since $s[\mathbf{S}]$ has been cancelled, the checkout message can never be received and so is removed from the queue (E-CANCELMSG). Similarly since both **C** and **PP** are waiting for messages from cancelled role **S**, they both evaluate their failure computations, **raise** (E-CANCELH). In turn this results in the cancellation of the *cust* and *pp* actors, and the $s[\mathbf{C}]$ and $s[\mathbf{PP}]$ endpoints (E-RAISES).

$$\rightarrow^+ \mathcal{G} \left[\begin{array}{l} \zeta \text{shop} \parallel \zeta s[\mathbf{S}] \\ \parallel \langle \text{cust}, \mathbf{idle}(), (\mathbf{raise})^{s[\mathbf{C}]}, \epsilon, \epsilon \rangle \\ \parallel \langle \text{pp}, \mathbf{idle}(), (\mathbf{raise})^{s[\mathbf{PP}]}, \epsilon, \epsilon \rangle \\ \parallel s \triangleright \epsilon \end{array} \right] \rightarrow^+ \mathcal{G} [\zeta \text{shop} \parallel \zeta s[\mathbf{S}] \parallel \zeta \text{cust} \parallel \zeta s[\mathbf{C}] \parallel \zeta \text{pp} \parallel \zeta s[\mathbf{PP}] \parallel s \triangleright \epsilon]$$

At this point the session has failed and can be garbage collected, leaving the supervisor actor and the zapper thread for *shop*. Since the supervisor was monitoring *shop*, which has crashed, the monitor callback is invoked (E-INVOKEM) which finally re-spawns and monitors the Shop actor.

$$\rightarrow (vshop)(vsup) \left(\begin{array}{l} \zeta \text{shop} \\ \parallel \langle \text{sup}, \text{shopSup } cAP (), \epsilon, \epsilon, \epsilon \rangle \end{array} \right) \rightarrow^+ (vshop')(vsup) \left(\begin{array}{l} \langle \text{shop}', \text{shop } (cAP, \text{initialStock}), \epsilon, \epsilon, \epsilon \rangle \\ \parallel \langle \text{sup}, \mathbf{idle}(), \epsilon, \epsilon, (\text{shop}', \text{shopSup } cAP) \rangle \end{array} \right)$$

Runtime syntax

Cancellation-aware runtime envs. $\Phi ::= \cdot \mid \Phi, p \mid \Phi, i^\pm : S \mid \Phi, s[p] : S \mid \Phi, s[p] : \cancel{\cdot} \mid \Phi, s : Q$
 Labels $\gamma ::= \dots \mid \cancel{\cdot} s[p] \mid s : p \cancel{\cdot} q : \ell \mid s : p \cancel{\cdot} q$

Modified typing rules for configurations

$\frac{\Gamma, a : \text{Pid}; \Phi, a \vdash C}{\Gamma; \Phi \vdash (va)C}$	$\frac{\Gamma, a \vdash \cancel{\cdot} a}{\Gamma; a \vdash \cancel{\cdot} a}$	$\frac{\Gamma; s[p] : \cancel{\cdot} \vdash \cancel{\cdot} s[p]}{\Gamma; s[p] : \cancel{\cdot} \vdash \cancel{\cdot} s[p]}$	$\frac{\Gamma; i^\pm : S \vdash \cancel{\cdot} i}{\Gamma; i^\pm : S \vdash \cancel{\cdot} i}$
$\frac{\Gamma; \Phi_1 \mid C \vdash \mathcal{T} \quad \Gamma; \Phi_2 \mid C \vdash \sigma \quad \Gamma; \Phi_3 \mid C \vdash \rho \quad \forall (b, V) \in \omega. \Gamma \vdash b : \text{Pid} \wedge \Gamma \vdash V : C \xrightarrow{C} C}{\Gamma; \Phi_1, \Phi_2, \Phi_3, a \vdash \langle a, \mathcal{T}, \sigma, \rho, \omega \rangle}$	$\frac{\Gamma \vdash V : \text{Handler}(S^2, C) \quad \Gamma \vdash W : C \xrightarrow{C} C \quad \Gamma; \Phi \mid C \vdash \sigma}{\Gamma; \Phi, s[p] : S^2 \mid C \vdash \sigma[s[p] \mapsto (V, W)]}$		

Additional LTS rules

LBL-ZAPMSG	$\Phi, s[q] : \cancel{\cdot}, s : (p, q, \ell(A)) \cdot Q$	$\xrightarrow{s:p \cancel{\cdot} q:\ell}$	$\Phi, s[q] : \cancel{\cdot}, s : Q$	
LBL-ZAPRECV	$\Phi, s[p] : q \& \{\ell_i(A_i) \cdot S_i\}_{i \in I}, s[q] : \cancel{\cdot}, s : Q$	$\xrightarrow{s:p \cancel{\cdot} q}$	$\Phi, s[p] : \cancel{\cdot}, s[q] : \cancel{\cdot}, s : Q$	(if $\text{messages}(q, p, Q) = \emptyset$)
LBL-ZAP	$\Phi, s[p] : S$	$\xrightarrow{s[p]}$	$\Phi, s[p] : \cancel{\cdot}$	

Fig. 15. $\text{Maty}_{\cancel{\cdot}}$: Modified configuration typing rules and type LTS

5.1 Metatheory

All metatheoretical results continue to hold. Figure 15 shows the necessary modifications to the configuration typing rules and type LTS. We extend runtime type environments to *cancellation-aware* environments Φ that include an additional entry of the form $s[p] : \cancel{\cdot}$, denoting that endpoint $s[p]$ has been cancelled. We also extend the type LTS to account for failure propagation [6]. Rule LBL-ZAP handles role cancellation (e.g. due to E-RAISES), but is defined separately since it is not needed for determining behavioural properties of types.

5.1.1 Preservation. We need to modify the preservation theorem to include role cancellation in environment reduction relation: specifically we write \Rightarrow for the relation $\Longrightarrow^? \rightsquigarrow^*$. The safety property is unchanged for cancellation-aware environments.

THEOREM 5.1 (PRESERVATION (\longrightarrow , $\text{MATY}_{\cancel{\cdot}}$)). *If $\Gamma; \Phi \vdash C$ with $\text{safe}(\Phi)$ and $C \longrightarrow \mathcal{D}$, then there exists some Φ' such that $\Phi \Rightarrow \Phi'$ and $\text{safe}(\Phi')$ and $\Gamma; \Phi' \vdash \mathcal{D}$.*

5.1.2 Progress. $\text{Maty}_{\cancel{\cdot}}$ enjoys progress since E-CANCELMSG discards messages that cannot be received, and E-CANCELMSG invokes the failure continuation whenever a message will never be sent due to a failure. Monitoring is orthogonal. The one change is that zipper threads for actors may remain if the actor name is free in an existing monitoring or initialisation callback. We require a slightly-adjusted deadlock-freedom property and canonical form to account for session failure.

Definition 5.2 (Deadlock-freedom and compliance ($\text{Maty}_{\cancel{\cdot}}$)). A runtime environment Φ is *deadlock-free*, written $\text{df}_{\cancel{\cdot}}(\Phi)$, if $\Phi \Longrightarrow^* \Phi' \not\Rightarrow$ implies that either $\Phi' = s : \epsilon$ or $\Phi' = (s[p_i] : \cancel{\cdot})_{i \in I}, s : \epsilon$.

A runtime environment Φ is *compliant*, written $\text{comp}_{\cancel{\cdot}}(\Phi)$, if $\text{safe}(\Phi)$ and $\text{df}_{\cancel{\cdot}}(\Phi)$.

Definition 5.3. A $\text{Maty}_{\cancel{\cdot}}$ configuration C is in *canonical form* if it can be written:

$$(\tilde{v}i)(\tilde{v}p_{i \in 1..l})(\tilde{v}s_{j \in 1..m})(\tilde{v}a_{k \in 1..n})(p_i(\chi_i)_{i \in 1..l} \parallel (s_j \triangleright \delta_j)_{j \in 1..m} \parallel \langle a_k, \mathcal{T}_k, \sigma_k, \rho_k, \omega_k \rangle_{k \in 1..n'-1} \parallel \widetilde{\cancel{\cdot}} \alpha)$$

with $(\cancel{\cdot} a_k)_{k \in n'..n}$ contained in $\widetilde{\cancel{\cdot}} \alpha$.

THEOREM 5.4 (PROGRESS (MATY_ℓ)). *If $\cdot; \vdash C$, then either there exists some \mathcal{D} such that $C \longrightarrow \mathcal{D}$, or C is structurally congruent to the following canonical form:*

$$(\bar{v}\bar{i})(\nu p_{i \in 1..m})(\nu a_{j \in 1..n})(p_1(\chi_1)_{i \in 1..m} \parallel \langle a_j, \mathbf{idle}(U_j), \epsilon, \rho_j, \omega_j \rangle_{j \in 1..n'-1} \parallel (\ell a_j)_{j \in n'..m})$$

5.1.3 Global Progress. A modified version of global progress holds: in every ongoing session, after a number of reductions, each session will either be cancelled or perform a communication action.

THEOREM 5.5 (GLOBAL PROGRESS (MATY_ℓ)). *If $\cdot; \vdash C$ where C is thread-terminating, then for every $s \in \text{ongoingSessions}(C)$, then there exist \mathcal{D} and \mathcal{D}_1 such that $C \equiv (\nu s)\mathcal{D}$ where $\mathcal{D} \xrightarrow{\tau^*} \mathcal{D}_1$ and either $\mathcal{D}_1 \xrightarrow{s}$, or $\mathcal{D}_1 \equiv \mathcal{D}_2$ for some \mathcal{D}_2 where $s \notin \text{ongoingSessions}(\mathcal{D}_2)$.*

5.2 Discussion

The semantics of **raise** follows the Erlang “let it crash” methodology that favours crashing upon errors over defensive programming: the cascading failure approach, where a crashed actor propagates its failure to others in a session, is common in affine-session-based works (e.g., [25, 40]) and follows the strategy of previous dynamically-checked Erlang implementations of session typing [22].

Cancellation is also flexible enough to support other failure-handling strategies: we can for example implement a **leave** V construct that allows an actor to exit a session and update its state to V *without* terminating, using the following reduction rule:

$$\langle a, (\mathcal{E}[\mathbf{leave} V])^{s[p]}, \sigma, \rho, \omega \rangle \longrightarrow \langle a, \mathbf{idle}(V), \sigma, \rho, \omega \rangle \parallel \ell s[p]$$

Maty’s combination of event-driven concurrency and cancellation also makes handling timeouts straightforward. We could for example extend the **suspend** $U V W$ construct to **suspend** $U V t W$, where t is some deadline and invoke the failure-handling computation if the deadline is missed. The failure-handling callback could then e.g. either retry or raise an exception. Indeed, Hou et al. [33] show how session cancellation can be used to enable flexible timed session types and we expect that their results could be incorporated into our design.

6 Implementation and Evaluation

6.1 Implementation

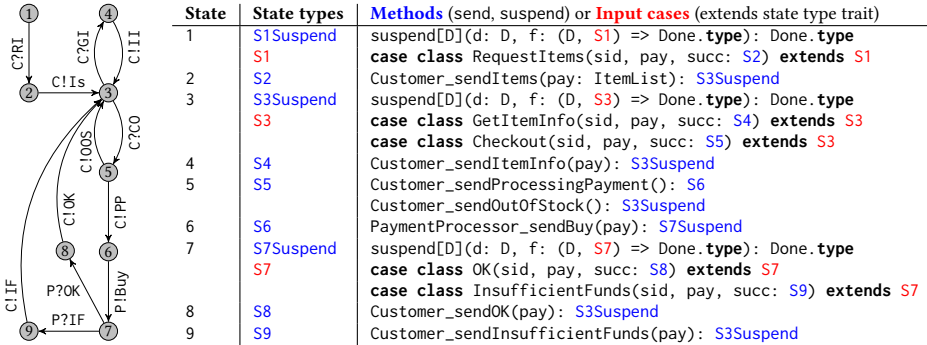
Based on our formal design, we have implemented a toolchain for Maty-style event-driven actor programming in Scala. It adopts the state machine based API generation approach of Scribble [35]:

- (1) The user specifies *global types* in the Scribble protocol description language [59].
- (2) Our toolchain internally uses Scribble to validate global types according to the MPST-based safety conditions, *project* them to local types for each role, and construct a representation of each local type based on *communicating finite state machines* (CFSM) [8].
- (3) From each CFSM, the toolchain generates a typed, *protocol-and-role-specific* API for the user to implement that role as an event-driven Maty actor in native Scala.

Typed APIs for Maty actor programming. Consider the **Shop** role in our running example (Fig. 6). Fig. 16 (top) shows the CFSM for **Shop** (with abbreviated message labels) and a summary of the main generated types and operations (omitting the type annotations for the `sid` and `pay` parameters). The toolchain generates Scala types for each CFSM state: non-blocking states (sends or suspends) are coloured **blue**, whereas blocking states (inputs) are **red**.

Non-blocking state types provide methods for outputs and suspend actions, with types specific to each state. The return type corresponds to the successor state type, enabling chaining of session actions: e.g., state type **S2** has method `Customer_sendItems` for the transition `C!Is`. The successor state type **S3Suspend** includes a `suspend` method to install a handler for the input event of state 3, and to yield control back to the event loop. The `Done.` type type ensures that each handler must

CFSM (left) and API (right) for Shop Role (left)



Implementation of Customer Request Handler for Shop Role

```

// d can be used for internal, _session-specific_ actor data
def custReqHandler[T: S1orS3](d: DataS, s: T): Done.type = {
  s match {
    case c: S1 => c match {
      // pay is message payload; succ is successor state
      case RequestItems(sid, pay, succ) =>
        succ.Customer_sendItems(d.summary())
        .suspend(d, custReqHandler[S3]) }
    case c: S3 => c match {
      case GetItemInfo(sid, pay, succ) =>
        succ.Customer_sendItemInfo(d.lookupItem(pay))
        .suspend(d, custReqHandler[S3])
      case Checkout(sid, pay, succ) =>
        if (d.inStock(pay)) {
          succ.Customer_sendProcessingPayment()
            .PaymentProcessor_sendBuy(d.total(pay))
            .suspend(d, paymentResponseHandler)
        }
    }
  }
}
// ...continuing on from the left column
} else {
  val sus = succ.Customer_sendOutOfStock()
  // d.staff: LOption[R1] -- this is a..
  // .."frozen" instance of state type R1
  d.staff match {
    // R1 is the Restock protocol state type
    case x: LSome[R1] =>
      ibecome(d, x, restockHndlr)
    case _: LNone =>
      // Error handling
      throw new RuntimeException
  }
  sus.suspend(d, custReqHandler[S3])
}
}
}

```

Fig. 16. API Generation for Customer-Shop-PaymentProcessor protocol

either complete the protocol or perform a suspend. Input state types are traits implemented by case classes generated for each input message. The event loop calls the user-specified handler with the corresponding case class upon each input event, with each case class carrying an instance of the successor state type. For example, S3 (state 3) is implemented by case classes GetItemInfo and Checkout for its input transitions, which respectively carry instances of successor states S4 and S5.

The API guides the user to build a Maty actor with handlers for every input event. Fig. 16 (bottom) handles S1 and can be passed to S1Suspend right after a session starts. It also handles S3 (for S3Suspend), where the shop receives GetItemInfo or Checkout. The runtime for our APIs executes sessions over TCP and uses the Java NIO library to run the actor event loops. It supports fully distributed sessions between remote Maty actors.

Switching between sessions. As well as supporting the core features and failure handling capabilities of Maty, our implementation also includes the ability to proactively switch between sessions. Figure 16 (bottom) shows how this functionality can be used to switch into a long-running Restock session when more stock is needed. For this purpose, the API allows the user to “freeze” unused state type instances as a type LOption[S] and resume them later by an inline ibecome. It allows the callback for a session switching behaviour to be performed inline with the currently active handler.

Discussion. Following our formal model, our generated APIs support a conventional style of actor programming where non-blocking operations are programmed in direct-style, in contrast to approaches that invert both input and output actions [57, 60] through the event loop.

Table 1. Selected case studies, examples from Savina, and key features of their Maty programs.

	MPST(s)			Maty actor programs									
	⊕/&	μ	C/P	mSA	mRA	PP	dSp	dTo	mAP	dAP	be	self	
Shop (Fig. 7)	✓	✓		✓	✓	✓			✓				
ShopRestock (Fig. 16)	✓	✓		✓	✓	✓			✓			✓	
Robot [23]	✓			✓		✓	✓	(✓)					
Chat [22]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Ping-self [38]	✓	✓	✓	✓	✓				✓		✓	✓	
Ping [38]	✓	✓											
Fib [37]				✓	✓	✓	✓	✓	✓	✓	✓		
Dining-self [38]	✓	✓	✓	✓	✓	✓	✓	(✓)	✓		✓	✓	
Dining [38]	✓	✓		✓	✓	✓	✓	(✓)	✓				
Sieve [38]	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	

⊕/& = Branch type(s) μ = Recursive type(s) C/P = Concurrent/Parallel types mSA = Multiple sessions/actor
mRA = Multiple roles/actor PP = Parameterised number of actors dSp = Dynamic actor spawning
dTo = Dynamic topology mAP = Multiple APs dAP = Dynamic AP creation be = ibecome self = Self communication

Static Scala typing ensures that handlers safely handle all possible input events at every stage (by exhaustive matching of case classes), and that state types offer only the permitted operations at each state (by method typing). Our API design requires *linear* usage of state type objects (e.g., `s` and `succ`) and frozen session instances. Following other works [11, 35, 50, 54, 58], we check linearity in a hybrid fashion: the Done return types in Fig. 16 statically require `suspend` to be invoked at least once, but our APIs rule out multiple uses *dynamically*. We exploit our formal support for failure handling (Sec. 5) to treat dynamic linearity errors as failures and retain safety and progress.

In summary, our toolchain enables Scala programming of Maty actors that support concurrent handling of multiple sessions, and ensures their safe execution. A statically well-typed actor will *never* select an unavailable branch or send/receive an incompatible payload type, and an actor system will *never* become stuck due to mismatching I/O actions. As in the theory, the system without `ibecome` will enjoy global progress provided every handler is terminating (e.g., by avoiding general recursion/infinite iteration). Although we make no formal claims about the system *with* `ibecome`, we conjecture that it will also enjoy progress up-to re-invocation of frozen sessions.

6.2 Evaluation

Table 1 summarises selected examples from the Savina [38] benchmark suite (lower) and larger case studies (upper); the extended version contains sequence diagrams for the larger examples. Notably, key design features of Maty, e.g. support for handling multiple sessions per actor (mSA) and implementing multiple protocols/roles within actors (mRA), are crucial to expressing many concurrency patterns.

The “-self” versions of Ping and Dining are versions faithful to the original Akka programs that involve internal coordination using `self ! msg` operations, but our APIs can express equivalent behaviour more simply without needing self-communication.

The (✓) distinguishes simpler forms of dynamic topologies (dTo) due to a parameterised number of clients dynamically connecting to a central server, from richer structures such as the parent-children tree topology dynamically created in Fib and the user-driven dynamic connections between clients and chat rooms in Chat; note both the latter involve dynamic access point creation (dAP).

The **Robot Coordination** use case (from Actyx AG [1], originally described in [23]) describes multiple Robots accessing a Warehouse with a single Door, where only one Robot is allowed in the Warehouse at a time. Maty allows the Door and Warehouse to safely handle the concurrent interleavings of events across *any number* (PP, dSP) of separate Robot sessions (mSA).

The **Chat Server** use case [22] involves an arbitrary number of Clients (PP) using a Registry to create new chat Rooms. Each Client can dynamically join and leave any existing Room. Rooms are created by spawning new Room actors (dSp) with fresh access points (dAP, mAP), and we allow any Client to establish sessions with the Registry or any Room asynchronously (dTo). We decompose

the Client-Registry and the Client-Room interactions into separate protocols (C/P, mAP), and use `ibecome` (`be`) in the Room actor to broadcast chat messages to all Clients currently in that Room.

7 Related Work

We have given an overview of previous work on session-typed actors in §1.3. Several works investigate event-driven session typing. Zhou et al. [60] introduce a multiparty session type discipline with statically-checked refinement types in $F\star$, using callbacks for each send and receive to avoid reasoning about linearity. Miu et al. [44] and Thiemann [57] adopt this approach for web applications and Agda [49] respectively. Our approach only yields control to the event loop on actor *receives*, as in idiomatic actor programming. Hu et al. [34] and Kouzapas et al. [39] introduce a binary session π -calculus with primitives for event loops; we instead encode the event loop directly in the semantics. Viering et al. [58] support fault-tolerant session-typed distributed programming with inversion of control on both input and outputs. They establish a version of global progress for trees of *subsessions* [17]; we instead establish global progress for every session in the system. These works all focus on process calculi rather than language design.

Ciccone et al. [14] developed *fair termination* for *synchronous* multiparty sessions, a strong property that subsumes our global progress: it implies every *role* fairly terminates, whereas our coarser-grained property is per *session*. Padovani and Zavattaro [51] developed fair termination for asynchronous *binary* sessions and show that fair termination implies orphan message freedom [13]. Our system ensures orphan message freedom for terminated multiparty sessions (as in [18, 20]), but we do not aim to restrict Maty to terminating sessions. We may be able to strengthen our formal results by adapting the fairness conditions discussed in [14, 51] (developed for session π -calculi) to our event-driven actor setting; however, features such as combining session creation and parallel composition into one term (based on linear logic) are more restrictive than in our model.

Mailbox types [16, 23] capture the expected contents of a mailbox as a commutative regular expression, and ensure that processes do not receive unexpected messages. Mailbox and session types both aim to ensure safe communication but address different problems: session types suit *structured* interactions among known participants, whereas mailbox types are better when participants are unknown and message ordering is unimportant. Mailbox types cannot yet handle failure.

Internal delegation [10] allows channels to migrate within a session, and may provide a way to relate our model to session π -calculi via encodings (cf. [39]). Barbanera et al. [4, 5] emphasise simplified, *compositional* multiparty session models, and it would be interesting to formally compare their approach (based on parallel composition and forwarding) to our single-threaded model.

Effpi [56] uses Scala's dependent function types to allow functions to be checked against interactions written in a type-level DSL, supporting verification of properties such as liveness and termination. This is different to session typing (e.g., supporting parameterised interactions but not branching), but it is unclear how their actor API would scale to multiple session-style interactions.

8 Conclusion and Future Work

This paper introduces Maty, an actor language that rules out communication mismatches and deadlocks using *multiparty session types*. Key to our approach is a novel combination of a flow-sensitive effect system and first-class message handlers. Maty scales to Erlang-style failure handling. Finally, we have shown an implementation of Maty in Scala using an API generation approach, and evaluated our implementation on two larger case studies and a selection of examples from the Savina benchmark suite. In future it would be interesting to investigate path-dependent types in our implementation, and to investigate finer-grained models for failure recovery (e.g., [47]).

Acknowledgements

We thank the anonymous OOPSLA reviewers for their thorough comments that greatly improved the quality of the paper. Thanks to Phil Trinder for his helpful comments on an early draft, and to Matthew Alan Le Brun and Alceste Scalas for discussions about the asynchronous semantics of multiparty session calculi. This work was supported by EPSRC Grant EP/T014628/1 (STARDUST).

Data Availability Statement

Our implementation is available on Zenodo [24].

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Received 2025-10-10; accepted 2026-02-17