Implementing Linking in Multiparty Sessions
(Extended Abstract)

Hanwen Wu
Dept. of Computer Science
Boston University
Boston, MA, USA
hwwu@bu.edu

Hongwei Xi
Dept. of Computer Science
Boston University
Boston, MA, USA
hwxi@bu.edu

Abstract
The fast growth of service-oriented programming (SOP) is evident in this day and age of the Internet, and handling communication is of paramount importance in SOP. Session types are a formalism that is proposed to specify interactions between communicating processes, where the word “session” loosely refers to a (possibly infinite) sequence of such interactions. In essence, a session type system is a kind of type system designed to enforce (through type-checking) that the involved processes communicate according to a chosen protocol specified as a session type. It is well-known that linear logic plays a pivotal role in the study of session types.

We have also formulated a novel multiparty session type system directly based on LMRL. When implementing it, we need to find a way of connecting multiple channels that corresponds to mp-cut. In this paper, we describe an implementation of linking for multiparty sessions in the setting of shared memory. We also describe two novel concepts, two-way linking with residual and three-way linking, which can only be formulated in the setting of multiparty sessions. Notably, linking for binary sessions can be thought of as a specially optimized version of what is implemented for multiparty sessions.

Keywords session types, concurrency, forwarding, linking

1 Introduction
Original session types [5, 6, 12] are binary in the sense that they are formulated for specifying communication protocols between exactly two parties, which are connected via a channel with two endpoints, usually held by some threads implementing the parties. As an example, let us assume that two programs P and Q are connected with a bi-directional channel. We may think of P as a client who sends two integers to the server Q and then receives from Q either true or false depending on whether or not the first sent integer is less than the second one. The communication protocol can be described using a session type of the following form:

\[
\text{msg}(P, \text{int}) :: \text{msg}(P, \text{int}) :: \text{msg}(Q, \text{bool}) :: \text{end}(P)
\]

which means that an integer is to be sent from P, another integer is to be sent from P, a boolean is to be sent from Q, and finally the channel is to be closed by P. The session type system will ensure P and Q implement the protocol dually from their respective local perspective. The session between P and Q is bounded in the sense that it contains only a bounded number of sends and receives. By introducing recursively defined session types, unbounded sessions containing indefinite numbers of sends and receives can be readily specified.

Figure 1 shows an example of two-way linking. Rectangles are threads, lines are channels, circles at both ends of a channel are its endpoints, and the number in an endpoint is the role to be played by the party holding the endpoint. In a binary session, there are only two roles, abstracted as 0 and 1. The middle thread performs a link in (Before), and the result is shown in (After) where the linking thread is removed from the middle. Linking may look like an unfamiliar feature as it is usually not seen in a message passing system that is not based on session types. This feature enables the composition of sessions in a well-defined way. In particular, one can only link two channels of the same session type, by connecting two dual endpoints and leaving the other two dual endpoints communicating directly as if they were the two endpoints of a newly formed channel.

While synchronous two-way linking may seem trivial to implement, any practical implementation of two-way linking is inherently asynchronous, where channels are buffered
and sending on such channels is non-blocking. Indeed asynchrony makes it difficult to merge two channels as there are potentially unreceived messages left in the buffers attached to them. Concurrent C0 [14] is a notable asynchronous implementation for a binary session type system that supports two-way linking. In a binary session, a channel is shared by exactly two parties/participants. This fact can be used to infer the direction of messages, which in turn indicates that only one channel may have unreceived messages. However, there is no such inference in the setting of multiparty sessions.

Multiparty session types [7] are introduced to specify sessions involving more than two participants. While the original work of [7] connects all the parties via a vector of point-to-point channels, we instead use a single channel to connect all endpoints here, essentially making the channel a message-bus or blackboard. In a multiparty session, all parties other than the ones involved in a link can be simultaneously writing/reading on the channel. Linking becomes completely symmetric and there is not a single unique direction of message flows. Also, the two channels being linked may both contain unreceived messages, making it difficult to merge them while preserving message orders. Based on our formulation of multiparty session types [15], a well-defined two-way linking with residual, or even three-way linking, is also possible. These features are essential in composing multiparty sessions [11, 16] but they are even more difficult to be implemented correctly.

We present an example of a three-player (denoted by the roles 0, 1, and 2) game similar to the one in [11] in Figure 2. Suppose player 1 (in the middle) would like to initiate the game but does not know the other players yet. When player 0 (on the left) comes, player 1 creates a channel, passing the endpoint of role 0 to player 0, while player 1 holds the dual/complement endpoint of roles 1 and 2. Similarly, player 1 gives endpoint 2 to player 2 while holding complement endpoint of roles 0 and 1. Now, to start the game, player 1 can perform a two-way linking with residual by merging the two endpoints that it holds into a single endpoint with residual roles. In this case, the residual role is the intersection of \{0, 1\} \cap \{1, 2\}, which equals \{1\}. Please see [15–17] for justification of the correctness of this initialization process based on multirole logic.

Alternatively, we can also rely on a dedicated game server to match a game for players (that do not know each other).

\[1\] It relates to the logical rule 2-cut-residual in multirole logic [17].

\[2\] The correctness of doing so is justified in multirole logic.

2 Run-time Implementation

Any multiparty session type system should come with, besides the type system itself, a runtime that implements channels and operations on channels, e.g., send, receive, and link. We briefly describe such an asynchronous runtime.

Channels are implemented as a blackboard, where any party can read messages that any other party writes. When implemented locally, the blackboard can be a shared buffer. When implemented distributedly, the blackboard can be a database. We abstract over this detail, only assuming the following properties. First, the blackboard is unbounded in capacity. Second, the blackboard should support atomic writes and atomic selective reads in the style of Erlang [1]. Selective receive is essential for guaranteeing the order of the received messages when there are multiple readers, writers, and kinds of messages. Third, the blackboard preserves the order of messages.

A message consists of a header and a body, where the header contains a label (denoting the kind of the message), the sender’s role, and the receivers’ roles. For instance, we may use MSG for synchronizing send/receive, BRANCH for synchronizing choose/offer, etc. Also, we use KILL and KEEP for linking. These header fields are essential. When combined with selective reads, they can guarantee the correct ordering of message exchanges. For instance, suppose…
both party 0 and party 2 send point-to-point messages of some label to party 1 asynchronously, then they may be written to the board in an unspecified order. Therefore simply returning the first message is not correct. We need to use selective receive based on the header in order to let party 1 deterministically retrieve the message based on the session type. Essentially, the combination of message headers and selective receive provides each endpoint a filtered view of the board, where only messages relevant to a party is present, and they are correctly ordered. Please note that message ordering is not an issue in a binary session. One only needs to guarantee a party does not read a message from the board that is just written by itself. For instance, Concurrent C0 [14] uses a direction flag for this purpose.

The receivers field of a message is also used for recording which party is yet to receive the message. For instance, a thread may hold an endpoint of roles \( \{0,1\} \). If the thread receives a point-to-point message for party 1, then only 1 will be removed from the receivers field of the message to mark it as read. If the thread receives a broadcast message, then both 0 and 1 will be removed. After all receiving parties have received the message, the receivers field becomes empty and thus can be removed from the blackboard. The receivers field of KEEP/KILL has particular usages and is not subject to “mark-as-read.”

The board provides, amongst others, two low-level APIs, read and write. Informally, read has a signature of \((\text{label, sender role, receiver roles}) \rightarrow \text{payload}\) and write has \((\text{label, sender role, receiver roles, payload}) \rightarrow \text{void}\). In our formulation of session types, the sender is always a single role, while receivers can be either a single role for point-to-point messaging, or the full set of roles w.r.t a session for broadcasting. When invoking read, one needs to specify the receiver(s) to work with “mark-as-read.” For instance, if a thread uses an endpoint to receive a broadcast message, it should invoke read with all the roles played by the endpoint. Note that read is selective, and we define a match as follows. Given a pattern, a message is a match if 1) the label is the same as the pattern, 2) the sender is the same as the pattern, 3) the receivers are a superset of that in the pattern. We say “match” from now on if these conditions are true. For KEEP/KILL, we check for a match only based on receivers and ignore labels and senders.

Each endpoint is a tuple of \((\text{roles}, \text{roles}, \text{reference to the board})\) plus a set of high-level APIs like send, receive, and link implemented using low-level ones like read/write of the board. The first field records the full set of roles w.r.t a session, while the second field is the subset of roles played by the endpoint. The thread holding the endpoint essentially plays these roles within the session. For instance, a thread holding endpoint \((\{0,1,2\},\emptyset, \text{Board 1})\) plays role 0 in a three-party session, where Board 1 is a pointer/reference to some shared-memory blackboard.

Blackboard is reference counted. Notably, the KEEP/KILL message also contains a counted reference to a blackboard that we shall detail later. When the reference count decreases to zero, the blackboard will be freed. Because of reference counting, session termination can be implemented asynchronously by allowing each endpoint to terminate on its own, as compared to a synchronized termination using a pair of functions like close/wait. Note again that a binary session does not need reference counted channels since it is always known to have exactly two parties in a session.

### 3 Two-way Linking in Multiparty Sessions

We describe the implementation of two-way linking in multiparty sessions. We start with two blackboards being linked as in Figure 4, each containing some messages unreceived. For instance, \([\text{MSG}] \ [f:t] \ \text{payload}\) means the message is of label MSG, with senders \(f\) (from), receivers \(t\) (to), and some payload. An important difference from linking in binary sessions is that both boards may contain messages needed by endpoints from the other boards. For instance, there may be messages needed by party 1 on both boards.

To merge two boards into one, we drain one board until it has no messages left, and reuse the other board as the resulting board. Since linking is entirely symmetric, we randomly pick a board as the keep board, and the other as a kill board. Let’s assume board 1 is the keep board, and board 2 is the kill board. We write a message “[KEEP] [f:0,1] Board 2” to the keep board, and a message “[KILL] [f:2] Board 1” to the kill board where the receivers of both messages are essentially the roles not involved in the link in their respective sessions, except that KEEP additionally contains the residual roles. The receivers field is especially important for avoiding self-loops and these roles are justified by session typing and LMRL. The sender fields are not used. Both messages have counted references to the other board as their payloads. In the meantime, the middle thread will obtain an endpoint (referencing the keep board) with residual roles. If the residual roles are empty, the endpoint can be immediately closed. Figure 5 shows what it looks like right after the linking function returns.

A crucial invariant is that KILL should be the last message in a board. Specifically, write follows KILL, but ignores KEEP. Namely, write appends to the end of a destination
write ensures that messages after KEEP to match any messages before read if KEEPing from the message right after the i.e., board 2. If readply needs to respect this order. Specifically, KEEPcorresponding KILLmerged. As a result, the implementation of KEEPbefore messages. By session typing, messages on both boards that come merged safely without breaking topological orders. With the above invariant, the corresponding implementation of write ensures that messages after KEEP are already properly merged. As a result, the implementation of read simply needs to respect this order. Specifically, read attempts to match any messages before KEEP or KILL first. Otherwise, if read sees a KEEP, it is redirected to the referenced board, i.e., board 2. If read fails again on board 2, it restarts searching from the message right after the KEEP on board 1. Additionally, if KILL is the only message left on board 2, the corresponding KEEP in board 1 is deleted since board 2 is no longer relevant. In the other case where read sees a KILL, it is redirected to the referenced board, i.e., board 1, if KILL is a match. Otherwise read fails if KILL is not a match, which only happens when the read is redirected by a corresponding KEEP. Reference counting ensures that boards are safely freed eventually.

It is very common to have a long chain of linking, e.g., the queue example given by [9]. It may result in a configuration like Figure 6. The presented approach is recursive and is valid in the presence of chaining. For instance, read or write can be redirected multiple times. Reference counting of boards guarantees that only when the board is irrelevant to any endpoints that it can be safely freed. The decision to put counted references in KEEP and KILL dramatically simplifies the implementation of linking in the presence of chaining.

Interestingly, since three-way linking can be implemented using two consecutive two-way linking with residual, chaining such as that in Figure 6 can be thought as a generalized three-way linking. Namely, to implement three-way linking directly, one simply need to insert two KEEP messages in the keep board, and one KILL for each of the other two kill boards, just like Figure 6.

### 4 Related Works and Conclusions

The most related implementations of session type systems are SILL [9] and Concurrent C0 [14] based on [3], and Session Links [8] based on [13]. Session Links does not support linking/forwarding. SILL uses explicit forwarding to our best knowledge. Concurrent C0 implements linking by sending a FWD, which is also mentioned in their recent work [10]. FWD is essentially our KILL. Because a binary session only has two parties, it can be shown based on session typing that the kill board will not have messages needed by parties referencing the keep board. Therefore there is no need for a KEEP message to redirect read to the kill board. With multiparty sessions, this inexplicit condition no longer holds, and both boards need to reference each other. Our prior work from late 2015 independently implemented linking in binary sessions by writing a board reference to another board. Implementation wise, the present paper draws inspirations from both our prior work and the work from Concurrent C0. With the present work, the implementation of Concurrent C0 can be thought as an optimized implementation for binary sessions, where KEEP and reference counting are not needed, and the linking thread always has empty residual roles allowing the thread to be removed.

Another related work is 1channels in [11]. In their 3-player game example, a server creates a private 3-party session. To start a game, the server sends out each endpoint to a player, via private channels between the server and each player. This is formulated as multiparty delegation/higher-order sessions. With our implementation, this can be done directly by linking, avoiding those private channels, and is arguably closer to real-world scenarios. [2, 4] uses arbiters, which are essentially explicit forwarding.

To conclude, we generalized the implementation of linking to multiparty sessions. We identified several additional requirements that are not needed in binary sessions. One needs the KEEP in addition to the KILL/FWD in order to redirect read from the keep board to the kill board. One needs message headers and selective receives for guaranteeing topological orders of messages. One needs references counting to decide when to free channels. We also identified two new primitives, two-way linking with residual and three-way linking. To justify their correctness, we have to refer readers to our prior work [15–17] due to space limits. To our best knowledge, the two new kinds of linking are novel, and the implementation of linking in multiparty session is also novel.

### References

[1] Joe Armstrong. 2003. Making reliable distributed systems in the presence of software errors. Ph.D. Dissertation. https://dblp.org/rec/phd/basesearch/Armstrong03

[2] Luís Caires and Jorge A Pérez. 2016. Multiparty Session Types Within a Canonical Binary Theory, and Beyond. FORTE (2016). https://doi.org/10.1007/978-3-319-39570-8_6
REFERENCES

[3] Luís Caires and Frank Pfenning. 2010. Session Types as Intuitionistic Linear Propositions.. In CONCUR. 
https://doi.org/10.1007/978-3-642-15375-4_16

[4] Marco Carbone, Sam Lindley, Fabrizio Montesi, Carsten Schürmann, and Philip Wadler. 2016. Coherence Generalises Duality - A Logical Explanation of Multiparty Session Types. CONCUR (2016). 
https://doi.org/10.4230/LIPIcs.CONCUR.2016.33

[5] Kohei Honda. 1993. Types for Dyadic Interaction.. In CONCUR. 
https://doi.org/10.1007/3-540-57208-2_35

[6] Kohei Honda, Vasco Thudichum Vasconcelos, and Makoto Kubo. 1998. Language Primitives and Type Discipline for Structured Communication-Based Programming.. In ESOP. 
https://doi.org/10.1007/BFb0053567

[7] Kohei Honda, Nobuko Yoshida, and Marco Carbone. 2008. Multiparty asynchronous session types. POPL (2008). 
https://doi.org/10.1145/1328438.1328472

[8] Sam Lindley and J Garrett Morris. 2015. Lightweight Functional Session Types. In Behavioural Types.

[9] Frank Pfenning and Dennis Griffith. 2015. Polarized Substructural Session Types.. In FoSSaCS. Springer, Berlin, Heidelberg, 3–22. 
https://doi.org/10.1007/978-3-662-46678-0_1

[10] F Pfenning and K PRUIKSMAN 2018. Asynchronous Multistructural Session Types. (2018). http://www.cs.cmu.edu/~fp/papers/multi18.pdf

[11] Alceste Scalas, Ornela Dardha, Raymond Hu, and Nobuko Yoshida. 2017. A Linear Decomposition of Multiparty Sessions for Safe Distributed Programming.. In ECOOP. 
https://doi.org/10.4230/LIPIcs.ECOOP.2017.24

[12] Kaku Takeuchi, Kohei Honda, and Makoto Kubo. 1994. An Interaction-based Language and its Typing System.. In PARLE. 
https://doi.org/10.1007/3-540-58184-7_118

[13] Philip Wadler. 2012. Propositions as sessions. ICFP (2012). 
https://doi.org/10.1145/2364527.2364568

[14] Max Willsey, Rokhini Prabhu, and Frank Pfenning. 2016. Design and Implementation of Concurrent C0.. In LINEARITY. 
https://doi.org/10.4204/EPTCS.238.8

[15] Hanwen Wu and Hongwei Xi. 2018. Multiparty Dependent Session Types (Extended Abstract). CoRR (2018). 
https://dblp.org/rec/journals/corr/abs-1808-00077

[16] Hongwei Xi and Hanwen Wu. 2016. Linearly Typed Dyadic Group Sessions for Building Multiparty Sessions. CoRR (2016). 
http://dblp.org/rec/journals/corr/XiW16

[17] Hongwei Xi and Hanwen Wu. 2017. Multirole Logic (Extended Abstract). CoRR (2017). http://dblp.org/rec/journals/corr/XiW17