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Caires, Luis; Pérez, Jorge A.; Pfenning, Frank; Toninho, Bernardo

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1 Domain-Aware Session Types

2 **Luís Caires** 


3 Universidade Nova de Lisboa

4 **Jorge A. Pérez** 

5 University of Groningen

6 **Frank Pfenning**

7 Carnegie Mellon University

8 **Bernardo Toninho** 

9 Universidade Nova de Lisboa

10 Abstract

11 We develop a generalization of existing Curry-Howard interpretations of (binary) session types
12 by relying on an extension of linear logic with features from *hybrid logic*, in particular modal worlds
13 that indicate *domains*. These worlds govern *domain migration*, subject to a parametric accessibility
14 relation familiar from the Kripke semantics of modal logic. The result is an expressive new typed
15 process framework for domain-aware, message-passing concurrency. Its logical foundations ensure
16 that well-typed processes enjoy session fidelity, global progress, and termination. Typing also ensures
17 that processes only communicate with accessible domains and so respect the accessibility relation.

18 Remarkably, our domain-aware framework can specify scenarios in which domain information
19 is available only at runtime; flexible accessibility relations can be cleanly defined and statically
20 enforced. As a specific application, we introduce domain-aware *multiparty session types*, in which
21 global protocols can express arbitrarily nested sub-protocols via domain migration. We develop a
22 precise analysis of these multiparty protocols by reduction to our binary domain-aware framework:
23 complex domain-aware protocols can be reasoned about at the right level of abstraction, ensuring
24 also the principled transfer of key correctness properties from the binary to the multiparty setting.

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34 1 Introduction

35 The goal of this paper is to show how existing Curry-Howard interpretations of session
36 types [10, 11] can be generalized to a *domain-aware* setting by relying on an extension of
37 linear logic with features from *hybrid logic* [40, 5]. These extended logical foundations of
38 message-passing concurrency allow us to analyze complex domain-aware concurrent systems
39 (including those governed by multiparty protocols) in a precise and principled manner.

40 Software systems typically rely on *communication* between heterogeneous services; at their
41 heart, these systems rely on message-passing protocols that combine mobility, concurrency,
42 and distribution. As distributed services are often virtualized, protocols should span diverse
43 software and hardware *domains*. These domains can have multiple interpretations, such as
44 the location where services reside, or the principals on whose behalf they act. Concurrent



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45 behavior is then increasingly *domain-aware*: a partner’s potential for interaction is influenced
 46 not only by the domains it is involved in at various protocol phases (its context), but also
 47 by *connectedness* relations among domains. Moreover, domain architectures are rarely fully
 48 specified: to aid modularity and platform independence, system participants (e.g., developers,
 49 platform vendors, service clients) often have only partial views of actual domain structures.
 50 Despite their importance in communication correctness and trustworthiness at large, the
 51 formal status of domains within *typed* models of message-passing systems remains unexplored.

52 This paper contributes to typed approaches to the analysis of domain-aware commu-
 53 nications, with a focus on *session-based concurrency*. This approach specifies the intended
 54 message-passing protocols as *session types* [30, 31, 24]. Different type theories for *binary*
 55 and *multiparty* (n -ary) protocols have been developed. In both cases, typed specifications
 56 can be conveniently coupled with π -calculus processes [36], in which so-called session chan-
 57 nels connect exactly two subsystems. Communication correctness usually results from two
 58 properties: *session fidelity* (type preservation) and *deadlock freedom* (progress). The former
 59 says that well-typed processes always evolve to well-typed processes (a safety property); the
 60 latter says that well-typed processes will never get into a stuck state (a liveness property).

61 A key motivation for this paper is the sharp contrast between (a) the growing relevance
 62 of domain-awareness in message-passing, concurrent systems and (b) the expressiveness of
 63 existing session type frameworks, binary and multiparty, which cannot adequately specify
 64 (let alone enforce) domain-related requirements. Indeed, existing session types frameworks,
 65 including those based on Curry-Howard interpretations [10, 47, 14], capture communication
 66 behavior at a level of abstraction in which even basic domain-aware assertions (e.g., “*Shipper*
 67 resides in domain *AmazonUS*”) cannot be expressed. As an unfortunate consequence, the
 68 effectiveness of the analysis techniques derived from these frameworks is rather limited.

69 To better illustrate our point, consider a common distributed design pattern: a middleware
 70 agent (*mw*) which answers requests from clients (*c1*), sometimes offloading the requests to a
 71 server (*serv*) to better manage local resource availability. In the framework of multiparty
 72 session types [32] this protocol can be represented as the global type:

$$\begin{aligned} \text{c1} \rightarrow \text{mw} : \{ \text{request} \langle \text{req} \rangle . \text{mw} \rightarrow \text{c1} : \{ \text{reply} \langle \text{ans} \rangle . \text{mw} \rightarrow \text{serv} : \{ \text{done} . \text{end} \} , \text{wait} . \text{mw} \rightarrow \text{serv} : \{ \text{req} \langle \text{data} \rangle . \\ \text{serv} \rightarrow \text{mw} : \{ \text{reply} \langle \text{ans} \rangle . \text{mw} \rightarrow \text{c1} : \{ \text{reply} \langle \text{ans} \rangle . \text{end} \} \} \} \} \} \end{aligned}$$

73 The client first sends a request to the middleware, which answers back with either a *reply*
 74 message containing the answer or a *wait* message, signaling that the server will be contacted to
 75 produce the final *reply*. While this multiparty protocol captures the intended communication
 76 behavior, it does not capture that protocols for the middleware and the server often involve
 77 some form of privilege escalation or specific authentication—ensuring, e.g., that the server
 78 interaction is adequately isolated from the client, or that the escalation must precede the
 79 server interactions. These requirements simply cannot be represented in existing frameworks.

80 Our work addresses this crucial limitation by generalizing Curry-Howard interpretations
 81 of session types by appealing to hybrid logic features. We develop a logically motivated
 82 typed process framework in which *worlds* from modal logics precisely and uniformly define
 83 the notion of *domain* in session-based concurrency. At the level of *binary* sessions, domains
 84 manifest themselves through point-to-point domain migration and communication. In
 85 *multiparty* sessions, domain migration is specified choreographically through the new construct
 86 \mathbf{p} moves $\tilde{\mathbf{q}}$ to ω for $G_1 ; G_2$, where participant \mathbf{p} leads a migration of participants $\tilde{\mathbf{q}}$ to domain
 87 ω in order to perform protocol G_1 , who then migrate back to perform protocol G_2 .

88 Consider the global type *Offload* $\triangleq \text{mw} \rightarrow \text{serv} : \{ \text{req} \langle \text{data} \rangle . \text{serv} \rightarrow \text{mw} : \{ \text{reply} \langle \text{ans} \rangle . \text{end} \} \}$
 89 in our previous example. Our framework allows us to refactor the global type above as:

$$\begin{aligned} \text{c1} \rightarrow \text{mw} : \{ \text{request} \langle \text{req} \rangle . \text{mw} \rightarrow \text{c1} : \{ \text{reply} \langle \text{ans} \rangle . \text{mw} \rightarrow \text{serv} : \{ \text{done} . \text{end} \} , \text{wait} . \text{mw} \rightarrow \text{serv} : \{ \text{init} . \\ \text{mw moves serv to } w_{\text{priv}} \text{ for Offload ; mw} \rightarrow \text{c1} : \{ \text{reply} \langle \text{ans} \rangle . \text{end} \} \} \} \} \end{aligned}$$

By considering a first-class multiparty domain migration primitive at the type and process levels, we can specify that the *offload* portion of the protocol takes place after the middleware and the server *migrate* to a private domain w_{priv} , as well as ensuring that only accessible domains can be interacted with. For instance, the type for the server that is mechanically *projected* from the protocol above ensures that the server first migrates to the private domain, communicates with the middleware, and then migrates back to its initial domain.

Perhaps surprisingly, our domain-aware *multiparty* sessions are studied within a context of logical *binary* domain-aware sessions, arising from a propositions-as-types interpretation of hybrid linear logic [22, 18], with strong static correctness guarantees derived from the logical nature of the system. Multiparty domain-awareness arises through an interpretation of multiparty protocols as *medium processes* [7] that orchestrate the multiparty interaction while enforcing the necessary domain-level constraints and migration steps.

Contributions The key contributions of this work are:

1. A process model with explicit domain-based migration (§2). We present a session π -calculus with domains that can be communicated via novel domain movement prefixes.
2. A session type discipline for domain-aware interacting processes (§3). Building upon an extension of linear logic with features from *hybrid logic* [22, 18] we generalize the Curry-Howard interpretation of session types [10, 11] by interpreting (*modal worlds* as *domains* where session behavior resides. In our system, types can specify domain *migration* and *communication*; domain mobility is governed by a parametric accessibility relation. Judgments stipulate the services used and realized by processes *and* the domains where sessions should be present. Our type discipline statically enforces session fidelity, global progress and, notably, that communication can only happen between accessible domains.
3. As a specific application, we introduce a framework of domain-aware multiparty sessions (§4) that uniformly extends the standard multiparty session framework of [32] with domain-aware migration and communication primitives. Our development leverages our logically motivated domain-aware *binary* sessions (§3) to give a precise semantics to multiparty sessions through a (typed) *medium process* that acts as an orchestrator of domain-aware multiparty interactions, lifting the strong correctness properties of typed processes to the multiparty setting. We show that mediums soundly and completely encode the local behaviors of participants in a domain-aware multiparty session.

We conclude with a discussion of related work (§5) and concluding remarks (§6).

2 Process Model

We introduce a synchronous π -calculus [42] with labeled choice and explicit domain migration and communication. We write $\omega, \omega', \omega''$ to stand for a concrete domain (w, w', \dots) or a domain variable (α, α', \dots) . Domains are handled at a high-level of abstraction, with their identities being attached to session channels. Just as the π -calculus allows for communication over names and name mobility, our model also allows for domain communication and mobility. These features are justified with the typing discipline of §3.

► **Definition 2.1.** *Given infinite, disjoint sets Λ of names (x, y, z, u, v) , \mathcal{L} of labels l_1, l_2, \dots , \mathcal{W} of domain tags (w, w', w'') and \mathcal{V} of domain variables (α, β, γ) , respectively, the set of processes (P, Q, R) is defined by*

$$\begin{array}{l}
 P ::= \mathbf{0} \quad | \quad P \mid Q \quad | \quad (\nu y)P \quad | \quad x(y).P \quad | \quad x(y).P \quad | \quad !x(y).P \\
 \quad | \quad [x \leftrightarrow y] \quad | \quad x \triangleright \{l_i : P_i\}_{i \in I} \quad | \quad x \triangleleft l_i; P \\
 \quad | \quad x(y@w).P \quad | \quad x(y@w).P \quad | \quad x(w).P \quad | \quad x(\alpha).P
 \end{array}$$

134 Domain-aware prefixes are present only in the last line. As we make precise in the typed
 135 setting of §3, these constructs realize mobility and domain communication, in the usual sense
 136 of the π -calculus: migration to a domain is always associated to mobility with a fresh name.

137 The operators $\mathbf{0}$ (inaction), $P \mid Q$ (parallel composition) and $(\nu y)P$ (name restriction)
 138 are standard. We then have $x\langle y \rangle.P$ (send y on x and proceed as P), $x(y).P$ (receive z on x
 139 and proceed as P with parameter y replaced by z), and $!x(y).P$ which denotes replicated
 140 (persistent) input. The forwarding construct $[x \leftrightarrow y]$ equates x and y ; it is a primitive
 141 representation of a copycat process. The last two constructs in the second line define a
 142 labeled choice mechanism: $x \triangleright \{l_i : P_i\}_{i \in I}$ is a process that awaits some label l_j (with $j \in I$)
 143 and proceeds as P_j . Dually, the process $x \triangleleft l_i; P$ emits a label l_i and proceeds as P .

144 The first two operators in the third line define explicit domain migration: given a domain
 145 ω , $x\langle y @ \omega \rangle.P$ denotes a process that is prepared to migrate the communication actions in P
 146 on endpoint x , to session y on ω . Complementarily, process $x(y @ \omega).P$ signals an endpoint x
 147 to move to ω , providing P with the appropriate session endpoint that is then bound to y . In
 148 a typed setting, domain movement will be always associated with a fresh session channel.
 149 Alternatively, this form of coordinated migration can be read as an explicit form of agreement
 150 (or authentication) in trusted domains. Finally, the last two operators in the third line define
 151 output and input of domains, $x\langle \omega \rangle.P$ and $x(\alpha).P$, respectively. These constructs allow for
 152 domain information to be obtained and propagated across processes dynamically.

153 Following [41], we abbreviate $(\nu y)x\langle y \rangle$ and $(\nu y)x\langle y @ \omega \rangle$ as $\bar{x}\langle y \rangle$ and $\bar{x}\langle y @ \omega \rangle$, respectively.
 154 In $(\nu y)P$, $x(y).P$, and $x(y @ \omega).P$ the distinguished occurrence of name y is binding with
 155 scope P . Similarly for α in $x(\alpha).P$. We identify processes up to consistent renaming of bound
 156 names and variables, writing \equiv_α for this congruence. $P\{x/y\}$ denotes the capture-avoiding
 157 substitution of x for y in P . While *structural congruence* \equiv expresses standard identities on
 158 the basic structure of processes (cf. [9]), *reduction* expresses their behavior.

159 *Reduction* ($P \rightarrow Q$) is the binary relation defined by the rules below and closed under
 160 structural congruence; it specifies the computations that a process performs on its own.

$$\begin{array}{ll}
 x\langle y \rangle.Q \mid x(z).P \rightarrow Q \mid P\{y/z\} & x\langle y \rangle.Q \mid !x(z).P \rightarrow Q \mid P\{y/z\} \mid !x(z).P \\
 x\langle y @ \omega \rangle.P \mid x(z @ \omega').Q \rightarrow P \mid Q\{y/z\} & x\langle \omega \rangle.P \mid x(\alpha).Q \rightarrow P \mid Q\{\omega/\alpha\} \\
 (\nu x)([x \leftrightarrow y] \mid P) \rightarrow P\{y/x\} & Q \rightarrow Q' \Rightarrow P \mid Q \rightarrow P \mid Q' \\
 P \rightarrow Q \Rightarrow (\nu y)P \rightarrow (\nu y)Q & x \triangleleft l_j; P \mid x \triangleright \{l_i : Q_i\}_{i \in I} \rightarrow P \mid Q_j \quad (j \in I)
 \end{array}$$

162 For the sake of generality, reduction allows dual endpoints with the same name to interact,
 163 independently of the domains of their subjects. The type system introduced next will ensure,
 164 among other things, *local reductions*, disallowing synchronisations among distinct domains.

165 3 Domain-aware Session Types via Hybrid Logic

166 This section develops a new domain-aware formulation of binary session types. Our system
 167 is based on a Curry-Howard interpretation of a linear variant of so-called *hybrid logic*, and
 168 can be seen as an extension of the interpretation of [10, 11] to hybrid (linear) logic. Hybrid
 169 logic is often used as an umbrella term for a class of logics that extend the expressiveness of
 170 propositional logic by considering modal *worlds* as syntactic objects that occur in propositions.

171 As in [10, 11], propositions are interpreted as session types of communication channels,
 172 proofs as typing derivations, and proof reduction as process communication. As main
 173 novelties, here we interpret: logical worlds as *domains*; the hybrid connective $@_\omega A$ as the
 174 type of a session that *migrates* to an accessible domain ω ; and type-level quantification over
 175 worlds $\forall \alpha.A$ and $\exists \alpha.A$ as *domain communication*. We also consider a type-level operator

176 $\downarrow\alpha.A$ (read “here”) which binds the *current* domain of the session to α in A . The syntax of
 177 domain-aware session types is given in Def. 3.1, where w, w_1, \dots stand for domains drawn
 178 from \mathcal{W} , and where α, β and ω, ω' are used as in the syntax of processes.

179 ► **Definition 3.1** (Domain-aware Session Types). *The syntax of types (A, B, C) is defined by*

$$180 \quad \begin{array}{l} A ::= \mathbf{1} \quad | \quad A \multimap B \quad | \quad A \otimes B \quad | \quad \&\{l_i : A_i\}_{i \in I} \quad | \quad \oplus\{l_i : A_i\}_{i \in I} \quad | \quad !A \\ \quad | \quad @_\omega A \quad | \quad \forall\alpha.A \quad | \quad \exists\alpha.A \quad | \quad \downarrow\alpha.A \end{array}$$

181 Types are the propositions of intuitionistic linear logic where the additives $A \& B$ and $A \oplus B$
 182 are generalized to a labelled n -ary variant. Propositions take the standard interpretation as
 183 session types, extended with hybrid logic operators [5], with worlds interpreted as domains
 184 that are explicitly subject to an *accessibility relation* (in the style of [43]) that is tracked
 185 by environment Ω . Intuitively, Ω is made up of direct accessibility hypotheses of the form
 186 $\omega_1 \prec \omega_2$, meaning that domain ω_2 is accessible from ω_1 .

187 Types are assigned to channel names; a *type assignment* $x:A[\omega]$ enforces the use of name
 188 x according to session A , *in the domain* ω . A *type environment* is a collection of type
 189 assignments. Besides the accessibility environment Ω just mentioned, our typing judgments
 190 consider two kinds of type environments: a *linear* part Δ and an *unrestricted* part Γ . They
 191 are subject to different structural properties: weakening and contraction principles hold for
 192 Γ but not for Δ . Empty environments are written as ‘ \cdot ’. We then consider two judgments:

$$193 \quad \text{(i) } \Omega \vdash \omega_1 \prec \omega_2 \quad \text{and} \quad \text{(ii) } \Omega; \Gamma; \Delta \vdash P :: z:A[\omega]$$

194 Judgment (i) states that ω_1 can directly access ω_2 under the hypotheses in Ω . We write
 195 \prec^* for the reflexive, transitive closure of \prec , and $\omega_1 \not\prec^* \omega_2$ when $\omega_1 \prec^* \omega_2$ does not hold.
 196 Judgment (ii) states that process P offers the session behavior specified by type A on
 197 channel z ; the session s resides at domain ω , under the accessibility hypotheses Ω , using
 198 unrestricted sessions in Γ and linear sessions in Δ . Note that each hypothesis in Γ and Δ is
 199 labeled with a specific domain. We omit Ω when it is clear from context.

200 **Typing Rules** Selected typing rules are given in Fig. 1; see [9] for the full listing. Right
 201 rules (marked with R) specify how to *offer* a session of a given type, left rules (marked
 202 with L) define how to *use* a session. The hybrid nature of the system induces a notion of
 203 *well-formedness* of sequents: a sequent $\Omega; \Gamma; \Delta \vdash P :: z : C[\omega_1]$ is *well-formed* if $\Omega \vdash \omega_1 \prec^* \omega_2$
 204 for every $x:A[\omega_2] \in \Delta$, which we abbreviate as $\Omega \vdash \omega_1 \prec^* \Delta$, meaning that all domains
 205 mentioned in Δ are accessible from ω_1 (not necessarily in a single *direct* step). No such
 206 domain requirement is imposed on Γ . If an end sequent is well-formed, every sequent in its
 207 proof will also be well-formed. All rules (read bottom-up) preserve this invariant; only (cut),
 208 (copy), (@R), (\forall L) and (\exists R) require explicit checks, which we discuss below. This invariant
 209 statically excludes interaction between sessions in accessible domains (cf. Theorem 3.7).

210 We briefly discuss some of the typing rules, first noting that we consider processes modulo
 211 structural congruence; hence, typability is closed under \equiv by definition. Type $A \multimap B$
 212 denotes a session that inputs a session of type A and proceeds as B . To offer $z:A \multimap B$ at
 213 domain ω , we input y along z that will offer A at ω and proceed, now offering $z:B$ at ω :

$$214 \quad \text{(\multimap R)} \quad \frac{\Omega; \Gamma; \Delta, y:A[\omega] \vdash P :: z:B[\omega]}{\Omega; \Gamma; \Delta \vdash z(y).P :: z:A \multimap B[\omega]} \quad \text{(\otimes R)} \quad \frac{\Omega; \Gamma; \Delta_1 \vdash P :: y:A[\omega] \quad \Omega; \Gamma; \Delta_2 \vdash Q :: z:B[\omega]}{\Omega; \Gamma; \Delta_1, \Delta_2 \vdash \bar{z}(y).(P \mid Q) :: z:A \otimes B[\omega]}$$

215 Dually, $A \otimes B$ denotes a session that outputs a session that will offer A and continue as B .
 216 To offer $z:A \otimes B$, we output a fresh name y with type A along z and proceed offering $z:B$.

217 The (cut) rule allows us to compose process P , which offers $x:A[\omega_2]$, with process Q ,
 218 which uses $x:A[\omega_2]$ to offer $z:C[\omega_1]$. We require that domain ω_2 is accessible from ω_1 (i.e.,
 219 $\omega_1 \prec^* \omega_2$). We also require $\omega_1 \prec^* \Delta_1$: the domains mentioned in Δ_1 (the context for P)
 220 must be accessible from ω_1 , which follows from the transitive closure of the accessibility
 221 relation (\prec^*) using the intermediary domain ω_2 . As in [10, 11], composition binds the name
 222 x :

$$223 \quad (\text{cut}) \frac{\Omega \vdash \omega_1 \prec^* \omega_2 \quad \Omega \vdash \omega_1 \prec^* \Delta_1 \quad \Omega; \Gamma; \Delta_1 \vdash P :: x:A[\omega_2] \quad \Omega; \Gamma; \Delta_2, x:A[\omega_2] \vdash Q :: z:C[\omega_1]}{\Omega; \Gamma; \Delta_1, \Delta_2 \vdash (\nu x)(P \mid Q) :: z:C[\omega_1]}$$

224 Type **1** means that no further interaction will take place on the session; names of type **1**
 225 may be passed around as opaque values. $\&\{l_i : A_i\}_{i \in I}$ types a session channel that offers
 226 its partner a choice between the A_i behaviors, each uniquely identified by a label l_i . Dually,
 227 $\oplus\{l_i : A_i\}_{i \in I}$ types a session that selects some behavior A_i by emitting the corresponding
 228 label. For flexibility and consistency with merge-based projectability in multiparty session
 229 types, rules for choice and selection induce a standard notion of session subtyping [26].

230 Type $!A$ types a shared (non-linear) channel, to be used by a server for spawning an
 231 arbitrary number of new sessions (possibly none), each one conforming to type A .

232 Following our previous remark on well-formed sequents, the only rules that appeal to
 233 accessibility are (@R), (@L), (copy), and (cut). These conditions are directly associated with
 234 varying degrees of flexibility in terms of typability, depending on what relationship is imposed
 235 between the domain to the left and to the right of the turnstile in the left rules. Notably, our
 236 system leverages the accessibility judgment to enforce that communication is only allowed
 237 between processes whose sessions are in (transitively) *accessible* domains.

238 The type operator $@_\omega$ realizes a *domain migration* mechanism which is specified both
 239 at the level of types and processes via name mobility tagged with a domain name. Thus, a
 240 channel typed with $@_{\omega_2}A$ denotes that behavior A is available by first *moving to* domain ω_2 ,
 241 directly accessible from the current domain. More precisely, we have:

$$242 \quad (\text{@R}) \frac{\Omega \vdash \omega_1 \prec \omega_2 \quad \Omega \vdash \omega_2 \prec^* \Delta \quad \Omega; \Gamma; \Delta \vdash P :: y:A[\omega_2]}{\Omega; \Gamma; \Delta \vdash \bar{z}\langle y@_{\omega_2} \rangle.P :: z:@_{\omega_2}A[\omega_1]} \quad (\text{@L}) \frac{\Omega, \omega_2 \prec \omega_3; \Gamma; \Delta, y:A[\omega_3] \vdash P :: z:C[\omega_1]}{\Omega; \Gamma; \Delta, x:@_{\omega_3}A[\omega_2] \vdash x(y@_{\omega_3}).P :: z:C[\omega_1]}$$

243 Hence, a process *offering* a behavior $z:@_{\omega_2}A$ at ω_1 ensures: (i) behavior A is available at ω_2
 244 along a *fresh* session channel y that is emitted along z and (ii) ω_2 is directly accessible from
 245 ω_1 . To maintain well-formedness of the sequent we also must check that all domains in Δ are
 246 still accessible from ω_2 . Dually, *using* a service $x:@_{\omega_3}A[\omega_2]$ entails receiving a channel y that
 247 will offer behavior A at domain ω_3 (and also allowing the usage of the fact that $\omega_2 \prec \omega_3$).

248 Domain-quantified sessions introduce domains as *fresh* parameters to types: a particular
 249 service can be specified with the ability to refer to any existing directly accessible domain
 250 (via universal quantification) or to some *a priori* unspecified accessible domain:

$$251 \quad (\forall R) \frac{\Omega, \omega_1 \prec \alpha; \Gamma; \Delta \vdash P :: z:A[\omega_1] \quad \alpha \notin \Omega, \Gamma, \Delta, \omega_1}{\Omega; \Gamma; \Delta \vdash z(\alpha).P :: z:\forall\alpha.A[\omega_1]} \quad (\forall L) \frac{\Omega \vdash \omega_2 \prec \omega_3 \quad \Omega; \Gamma; \Delta, x:A\{\omega_3/\alpha\}[\omega_2] \vdash Q :: z:C[\omega_1]}{\Omega; \Gamma; \Delta, x:\forall\alpha.A[\omega_2] \vdash x(\omega_3).Q :: z:C[\omega_1]}$$

252 Rule ($\forall R$) states that a process seeking to offer $\forall\alpha.A[\omega_1]$ denotes a service that is located
 253 at domain ω_1 but that may refer to any fresh domain directly accessible from ω_1 in its
 254 specification (e.g. through the use of @). Operationally, this means that the process must be
 255 ready to receive from its client a reference to the domain being referred to in the type, which
 256 is bound to α (occurring fresh in the typing derivation). Dually, Rule ($\forall L$) indicates that a

257 process interacting with a service of type $x:\forall\alpha.A[\omega_2]$ must make concrete the domain that
 258 is directly accessible from ω_2 it wishes to use, which is achieved by the appropriate output
 259 action. Rules $(\exists\text{L})$ and $(\exists\text{R})$ for the existential quantifier have a dual reading.

260 Finally, the type-level operator $\downarrow\alpha.A$ allows for a type to refer to its *current* domain:

$$261 \quad (\downarrow\text{R}) \frac{\Omega; \Gamma; \Delta \vdash P :: z:A\{\omega/\alpha\}[\omega]}{\Omega; \Gamma; \Delta \vdash P :: z:\downarrow\alpha.A[\omega]} \quad (\downarrow\text{L}) \frac{\Omega; \Gamma; \Delta, x:A\{\omega/\alpha\}[\omega] \vdash P :: z:C}{\Omega; \Gamma; \Delta, x:\downarrow\alpha.A[\omega] \vdash P :: z:C}$$

262 The typing rules that govern $\downarrow\alpha.A$ are completely symmetric and produce no action at the
 263 process level, merely instantiating the domain variable α with the current domain ω of the
 264 session. As will be made clear in §4, this connective plays a crucial role in ensuring the
 265 correctness of our analysis of multiparty domain-aware sessions in our logical setting.

266 By developing our type theory with an explicit domain accessibility judgment, we can
 267 consider the accessibility relation as a *parameter* of the framework. This allows changing
 268 accessibility relations and their properties without having to alter the entire system. To
 269 consider the simplest possible accessibility relation, the only defining rule for accessibility
 270 would be Rule (*whyp*) in Fig. 1. To consider an accessibility relation which is an equivalence
 271 relation we would add reflexivity, transitivity, and symmetry rules to the judgment.

272 **Discussion and Examples** Being an interpretation of *hybridized* linear logic, our domain-
 273 aware theory is *conservative* wrt the Curry-Howard interpretation of session types in [10, 11],
 274 in the following sense: the system in [10, 11] corresponds to the case where every session
 275 resides at the same domain. As in [10, 11], the sequent calculus for the underlying (hybrid)
 276 linear logic can be recovered from our typing rules by erasing processes and name assignments.

277 Conversely, a fundamental consequence of our hybrid interpretation is that it *refines* the
 278 session type structure in non-trivial ways. By requiring that communication only occurs
 279 between sessions located at the same (or accessible) domain we effectively introduce a new
 280 layer of reasoning to session type systems. To illustrate this feature, consider the following
 281 session type WStore , which specifies a simple interaction between a web store and its clients:

$$282 \quad \text{WStore} \triangleq \text{addCart} \multimap \&\{\text{buy} : \text{Pay}, \text{quit} : \mathbf{1}\} \quad \text{Pay} \triangleq \text{CCNum} \multimap \oplus\{\text{ok} : \text{Rcpt} \otimes \mathbf{1}, \text{nok} : \mathbf{1}\}$$

283 WStore allows clients to checkout their shopping carts by emitting a *buy* message or to *quit*.
 284 In the former case, the client pays for the purchase by sending their credit card data. If
 285 a banking service (not shown) approves the transaction (via an *ok* message), a receipt is
 286 emitted. Representable in existing session type systems (e.g. [10, 47, 31]), types WStore and
 287 Pay describe the intended communications but fail to capture the crucial fact that in practice
 288 the client's sensitive information should only be requested after entering a secure domain. To
 289 address this limitation, we can use type-level domain migration to *refine* WStore and Pay :

$$290 \quad \text{WStore}_{\text{sec}} \triangleq \text{addCart} \multimap \&\{\text{buy} : @_{\text{sec}} \text{Pay}_{\text{bnk}}, \text{quit} : \mathbf{1}\} \\ \text{Pay}_{\text{bnk}} \triangleq \text{CCNum} \multimap \oplus\{\text{ok} : (@_{\text{bnk}} \text{Rcpt}) \otimes \mathbf{1}, \text{nok} : \mathbf{1}\}$$

291 $\text{WStore}_{\text{sec}}$ decrees that the interactions pertinent to type Pay_{bnk} should be preceded by a
 292 migration step to the trusted domain sec , which should be directly accessible from $\text{WStore}_{\text{sec}}$'s
 293 current domain. The type also specifies that the receipt must originate from a bank domain
 294 bnk (e.g., ensuring that the receipt is never produced by the store without entering bnk).
 295 When considering the interactions with a client (at domain c) that checks out their cart, we
 296 reach a state that is typed with the following judgment:

$$297 \quad c \prec \text{ws}; \cdot; x:@_{\text{sec}} \text{Pay}_{\text{bnk}}[\text{ws}] \vdash \text{Client} :: z:@_{\text{sec}} \mathbf{1}[c]$$

$$\begin{array}{c}
\text{(whyp)} \frac{}{\Omega, \omega_1 \prec \omega_2 \vdash \omega_1 \prec \omega_2} \quad \text{(id)} \frac{}{\Omega; \Gamma; x:A[\omega] \vdash [x \leftrightarrow z] :: z:A[\omega]} \\
\text{(@R)} \frac{\Omega \vdash \omega_1 \prec \omega_2 \quad \Omega \vdash \omega_2 \prec^* \Delta \quad \Omega; \Gamma; \Delta \vdash P :: y:A[\omega_2]}{\Omega; \Gamma; \Delta \vdash \bar{z}(y@_{\omega_2}).P :: z:@_{\omega_2}A[\omega_1]} \quad \text{(@L)} \frac{\Omega, \omega_2 \prec \omega_3; \Gamma; \Delta, y:A[\omega_3] \vdash P :: z:C[\omega_1]}{\Omega; \Gamma; \Delta, x:@_{\omega_3}A[\omega_2] \vdash x(y@_{\omega_3}).P :: z:C[\omega_1]} \\
\text{(\forall R)} \frac{\Omega, \omega_1 \prec \alpha; \Gamma; \Delta \vdash P :: z:A[\omega_1] \quad \alpha \notin \Omega, \Gamma, \Delta, \omega_1}{\Omega; \Gamma; \Delta \vdash z(\alpha).P :: z:\forall\alpha.A[\omega_1]} \quad \text{(\forall L)} \frac{\Omega \vdash \omega_2 \prec \omega_3 \quad \Omega; \Gamma; \Delta, x:A\{\omega_3/\alpha\}[\omega_2] \vdash Q :: z:C[\omega_1]}{\Omega; \Gamma; \Delta, x:\forall\alpha.A[\omega_2] \vdash x(\omega_3).Q :: z:C[\omega_1]} \\
\text{(\exists R)} \frac{\Omega \vdash \omega_1 \prec \omega_2 \quad \Omega; \Gamma; \Delta \vdash P :: z:A\{\omega_2/\alpha\}[\omega_1]}{\Omega; \Gamma; \Delta \vdash z(\omega_2).P :: z:\exists\alpha.A[\omega_1]} \quad \text{(\exists L)} \frac{\Omega, \omega_2 \prec \alpha; \Gamma; \Delta, x:A[\omega_2] \vdash Q :: z:C[\omega_1]}{\Omega; \Gamma; \Delta, x:\exists\alpha.A[\omega_2] \vdash x(\alpha).Q :: z:C[\omega_1]} \\
\text{(\downarrow R)} \frac{\Omega; \Gamma; \Delta \vdash P :: z:A\{\omega/\alpha\}[\omega]}{\Omega; \Gamma; \Delta \vdash P :: z:\downarrow\alpha.A[\omega]} \quad \text{(\downarrow L)} \frac{\Omega; \Gamma; \Delta, x:A\{\omega/\alpha\}[\omega] \vdash P :: z:C}{\Omega; \Gamma; \Delta, x:\downarrow\alpha.A[\omega] \vdash P :: z:C} \\
\text{(copy)} \frac{\Omega \vdash \omega_1 \prec^* \omega_2 \quad \Omega; \Gamma, u:A[\omega_2]; \Delta, y:A[\omega_2] \vdash P :: z:C[\omega_1]}{\Omega; \Gamma, u:A[\omega_2]; \Delta \vdash \bar{u}(y).P :: z:C[\omega_1]} \\
\text{(cut)} \frac{\Omega \vdash \omega_1 \prec^* \omega_2 \quad \Omega \vdash \omega_2 \prec^* \Delta_1 \quad \Omega; \Gamma; \Delta_1 \vdash P :: x:A[\omega_2] \quad \Omega; \Gamma; \Delta_2, x:A[\omega_2] \vdash Q :: z:C[\omega_1]}{\Omega; \Gamma; \Delta_1, \Delta_2 \vdash (\nu x)(P \mid Q) :: z:C[\omega_1]}
\end{array}$$

■ **Figure 1** Typing Rules (Excerpt – see [9])

298 At this point, it is *impossible* for a (typed) client to interact with the behavior that is
299 protected by the domain `sec`, since it is not the case that $c \prec^* \text{sec}$. That is, no judgment
300 of the form $c \prec \text{ws}; \cdot; \text{Pay}_{\text{bnk}}[\text{sec}] \vdash \text{Client}' :: z:T[c]$ is derivable. This ensures, e.g., that a
301 client cannot exploit the payment platform of the web store by accessing the trusted domain
302 in unforeseen ways. The client can only communicate in the secure domain *after* the web
303 store service has migrated accordingly, as shown by the judgment

$$304 \quad c \prec \text{ws}, \text{ws} \prec \text{sec}; \cdot; x':\text{Pay}_{\text{bnk}}[\text{sec}] \vdash \text{Client}' :: z':1[\text{sec}].$$

305 **Technical Results** We state the main results of type safety via type preservation (The-
306 orem 3.3) and global progress (Theorem 3.4). These results directly ensure session fidelity
307 and deadlock-freedom. Typing also ensures termination, i.e., processes do not exhibit infinite
308 reduction paths (Theorem 3.5). We note that in the presence of termination, our progress
309 result ensures that communication actions are always guaranteed to take place. Moreover, as
310 a property specific to domain-aware processes, we show *domain preservation*, i.e., processes
311 respect their domain accessibility conditions (Theorem 3.7). The formal development of
312 these results relies on a *domain-aware* labeled transition system [9], defined as a simple
313 generalization of the early labelled transition system for the session π -calculus given in [10, 11].

315 **Type Safety and Termination.** Following [10, 11], our proof of type preservation relies on
316 a simulation between reductions in the session-typed π -calculus and logical proof reductions.

317 ► **Lemma 3.2** (Domain Substitution). *Suppose $\Omega \vdash \omega_1 \prec \omega_2$. Then we have:*

- 318 ■ *If $\Omega, \omega_1 \prec \alpha, \Omega'; \Gamma; \Delta \vdash P :: z:A[\omega]$ then*
319 $\Omega, \Omega'\{\omega_2/\alpha\}; \Gamma\{\omega_2/\alpha\}; \Delta\{\omega_2/\alpha\} \vdash P\{\omega_2/\alpha\} :: z:A[\omega\{\omega_2/\alpha\}].$
- 320 ■ *$\Omega, \alpha \prec \omega_2, \Omega'; \Gamma; \Delta \vdash P :: z:A[\omega]$ then*
321 $\Omega, \Omega'\{\omega_1/\alpha\}; \Gamma\{\omega_1/\alpha\}; \Delta\{\omega_1/\alpha\} \vdash P\{\omega_1/\alpha\} :: z:A[\omega\{\omega_1/\alpha\}].$

322 Safe domain communication relies on domain substitution preserving typing (Lemma 3.2).

323 ► **Theorem 3.3** (Type Preservation). *If $\Omega; \Gamma; \Delta \vdash P :: z:A[\omega]$ and $P \rightarrow Q$ then*

$$324 \quad \Omega; \Gamma; \Delta \vdash Q :: z:A[\omega].$$

325 **Proof (Sketch).** The proof mirrors those of [10, 11, 8, 44], relying on a series of lemmas
 326 relating the result of dual process actions (via our LTS semantics) with typable parallel
 327 compositions through the (cut) rule [9]. For session type constructors of [10], the results are
 328 unchanged. For the domain-aware session type constructors, the development is identical
 329 that of [8] and [44], which deal with communication of types and data terms, respectively. ◀

330 Following [10, 11], the proof of global progress relies on a notion of a *live* process, which
 331 intuitively consists of a process that has not yet fully carried out its ascribed session behavior,
 332 and thus is a parallel composition of processes where at least one is a non-replicated process,
 333 guarded by some action. Formally, we define $live(P)$ if and only if $P \equiv (\nu \tilde{n})(\pi.Q \mid R)$, for
 334 some R , names \tilde{n} and a non-replicated guarded process $\pi.Q$.

335 ▶ **Theorem 3.4** (Global Progress). *If $\Omega; \cdot; \cdot \vdash P :: x:1[\omega]$ and $live(P)$ then $\exists Q$ s.t. $P \rightarrow Q$.*

336 Note that Theorem 3.4 is without loss of generality since using the cut rules we can compose
 337 arbitrary well-typed processes together and x need not occur in P due to Rule (1R).

338 Termination (strong normalization) is a relevant property for interactive systems: while
 339 from a global perspective they are meant to run forever, at a local level participants should
 340 always react within a finite amount of time, and never engage into infinite internal behavior.
 341 We say that a process P *terminates*, noted $P \Downarrow$, if there is no infinite reduction path from P .

342 ▶ **Theorem 3.5** (Termination). *If $\Omega; \Gamma; \Delta \vdash P :: x:A[\omega]$ then $P \Downarrow$.*

343 **Proof (Sketch).** By adapting the *linear* logical relations given in [38, 39, 8]. For the system
 344 in §3 without quantifiers, the logical relations correspond to those in [38, 39], extended to
 345 carry over Ω . When considering quantifiers, the logical relations resemble those proposed for
 346 polymorphic session types in [8], noting that no impredicativity concerns are involved. ◀

347 **Domain Preservation.** As a consequence of the hybrid nature of our system, well-typed
 348 processes are guaranteed not only to faithfully perform their prescribed behavior in a deadlock-
 349 free manner, but they also do so without breaking the constraints put in place on domain
 350 accessibility given by our well-formedness constraint on sequents.

351 ▶ **Theorem 3.6.** *Let \mathcal{E} be a derivation of $\Omega; \Gamma; \Delta \vdash P :: z:A[\omega]$. If $\Omega; \Gamma; \Delta \vdash P :: z:A[\omega]$ is
 352 well-formed then every sub-derivation in \mathcal{E} well-formed.*

353 While inaccessible domains can appear in Γ , such channels can never be used and thus
 354 can not appear in a well-typed process due to the restriction on the (copy) rule. Combining
 355 Theorems 3.3 and 3.6 we can then show that even if a session in the environment changes
 356 domains, typing ensures that such a domain will be (transitively) accessible:

357 ▶ **Theorem 3.7.** *Let (1) $\Omega; \Gamma; \Delta, \Delta' \vdash (\nu x)(P \mid Q) :: z : A[\omega]$, (2) $\Omega; \Gamma; \Delta \vdash P :: x:B[\omega']$,
 358 and (3) $\Omega; \Gamma; \Delta', x:B[\omega'] \vdash Q :: z:A[\omega]$. If $(\nu x)(P \mid Q) \rightarrow (\nu x)(P' \mid Q')$ then: (a) $\Omega; \Gamma; \Delta \vdash$
 359 $P' :: x':B'[\omega'']$, for some x', B', ω'' ; (b) $\Omega; \Gamma, \Delta', x':B'[\omega''] \vdash Q' :: z:A[\omega]$; (c) $\omega \prec^* \omega''$.*

360 4 Domain-Aware Multiparty Session Types

361 We now shift our attention to multiparty session types [32]. We consider the standard
 362 ingredients: *global types*, *local types*, and the *projection function* that connects the two. Our
 363 global types include a new domain-aware construct, \mathfrak{p} moves \tilde{q} to ω for $G_1; G_2$; our local types
 364 exploit the hybrid session types from Def. 3.1. Rather than defining a separate type system
 365 based on local types for the process model of §2, our analysis of multiparty protocols extends

the approach defined in [7], which uses *medium processes* to characterize correct multiparty implementations. The advantages are twofold: on the one hand, medium processes provide a precise semantics for global types; on the other hand, they enable the principled transfer of the correctness properties established in §3 for binary sessions (type preservation, global progress, termination, domain preservation) to the multiparty setting. Below, *participants* are ranged over by $\mathbf{p}, \mathbf{q}, \mathbf{r}, \dots$; we write $\tilde{\mathbf{q}}$ to denote a finite set of participants $\mathbf{q}_1, \dots, \mathbf{q}_n$.

Besides the new domain-aware global type, our syntax of global types includes constructs from [32, 21]. We consider value passing in branching (cf. U below), fully supporting delegation. To streamline the presentation, we consider global types without recursion.

► **Definition 4.1** (Global and Local Types). *Define global types (G) and local types (T) as*

$$\begin{aligned} U &::= \text{bool} \mid \text{nat} \mid \text{str} \mid \dots \mid T \\ G &::= \text{end} \mid \mathbf{p} \rightarrow \mathbf{q} : \{l_i \langle U_i \rangle . G_i\}_{i \in I} \mid \mathbf{p} \text{ moves } \tilde{\mathbf{q}} \text{ to } \omega \text{ for } G_1 ; G_2 \\ T &::= \text{end} \mid \mathbf{p} ? \{l_i \langle U_i \rangle . T_i\}_{i \in I} \mid \mathbf{p} ! \{l_i \langle U_i \rangle . T_i\}_{i \in I} \mid \forall \alpha . T \mid \exists \alpha . T \mid @_{\alpha} T \mid \downarrow \alpha . T \end{aligned}$$

The completed global type is denoted end . Given a finite I and pairwise different labels, $\mathbf{p} \rightarrow \mathbf{q} : \{l_i \langle U_i \rangle . G_i\}_{i \in I}$ specifies that by choosing label l_i , participant \mathbf{p} may send a message of type U_i to participant \mathbf{q} , and then continue as G_i . We decree $\mathbf{p} \neq \mathbf{q}$, so reflexive interactions are disallowed. The global type $\mathbf{p} \text{ moves } \tilde{\mathbf{q}} \text{ to } \omega \text{ for } G_1 ; G_2$ specifies the migration of participants $\mathbf{p}, \tilde{\mathbf{q}}$ to domain ω in order to perform the *sub-protocol* G_1 ; this migration is lead by \mathbf{p} . Subsequently, all of $\mathbf{p}, \tilde{\mathbf{q}}$ migrate from ω back to their original domains and protocol G_2 is executed. This intuition will be made precise by the medium processes for global types (cf. Def. 4.8). Notice that G_1 and G_2 may involve different sets of participants. In writing $\mathbf{p} \text{ moves } \tilde{\mathbf{q}} \text{ to } \omega \text{ for } G_1 ; G_2$ we assume two natural conditions: (a) all migrating participants intervene in the sub-protocol (i.e., the set of participants of G_1 is exactly $\mathbf{p}, \tilde{\mathbf{q}}$) and (b) domain ω is accessible (via \prec) by all these migrating participants in G_1 . While subprotocols and session delegation may appear as similar, delegation supports a different idiom altogether, and has no support for domain awareness. Unlike delegation, with subprotocols we can specify a point where some of the participants perform a certain protocol *within the same multiparty session* and then return to the main session as an ensemble.

► **Definition 4.2.** *The set of participants of G (denoted $\text{part}(G)$) is defined as: $\text{part}(\text{end}) = \emptyset$, $\text{part}(\mathbf{p} \rightarrow \mathbf{q} : \{l_i \langle U_i \rangle . G_i\}_{i \in I}) = \{\mathbf{p}, \mathbf{q}\} \cup \bigcup_{i \in I} \text{part}(G_i)$, $\text{part}(\mathbf{p} \text{ moves } \tilde{\mathbf{q}} \text{ to } \omega \text{ for } G_1 ; G_2) = \{\mathbf{p}\} \cup \tilde{\mathbf{q}} \cup \text{part}(G_1) \cup \text{part}(G_2)$. We sometimes write $\mathbf{p} \in G$ to mean $\mathbf{p} \in \text{part}(G)$.*

Global types are projected onto participants so as to obtain local types. The terminated local type is end . The local type $\mathbf{p} ? \{l_i \langle U_i \rangle . T_i\}_{i \in I}$ denotes an offer of a set of labeled alternatives; the local type $\mathbf{p} ! \{l_i \langle U_i \rangle . T_i\}_{i \in I}$ denotes a behavior that chooses one of such alternatives. Exploiting the domain-aware framework in §3, we introduce four new local types. They increase the expressiveness of standard local types by specifying universal and existential quantification over domains ($\forall \alpha . T$ and $\exists \alpha . T$), migration to a specific domain ($@_{\alpha} T$), and a reference to the current domain ($\downarrow \alpha . T$, with α occurring in T).

We now define (*merge-based*) *projection* for global types [21]. To this end, we rely on a *merge* operator on local types, which in our case considers messages U .

► **Definition 4.3** (Merge). *We define \sqcup as the commutative partial operator on base and local types such that $\text{bool} \sqcup \text{bool} = \text{bool}$ (and analogously for other base types), and*

1. $T \sqcup T = T$, where T is one of the following: end , $\mathbf{p} ! \{l_i \langle U_i \rangle . T_i\}_{i \in I}$, $@_{\omega} T$, $\forall \alpha . T$, or $\exists \alpha . T$;
2. $\mathbf{p} ? \{l_k \langle U_k \rangle . T_k\}_{k \in K} \sqcup \mathbf{p} ? \{l'_j \langle U'_j \rangle . T'_j\}_{j \in J} =$
 $\mathbf{p} ? (\{l_k \langle U_k \rangle . T_k\}_{k \in K \setminus J} \cup \{l'_j \langle U'_j \rangle . T'_j\}_{j \in J \setminus K} \cup \{l_i \langle U_i \sqcup U'_i \rangle . (T_i \sqcup T'_i)\}_{i \in K \cap J})$
and is undefined otherwise.

410 Therefore, for $U_1 \sqcup U_2$ to be defined there are two options: (a) U_1 and U_2 are identical
 411 base, terminated, selection, or “hybrid” local types; (b) U_1 and U_2 are branching types, but
 412 not necessarily identical: they may offer different options but with the condition that the
 413 behavior in labels occurring in both U_1 and U_2 must be mergeable.

414 To define projection and medium processes for the global type \mathbf{p} moves $\tilde{\mathbf{q}}$ to ω for $G_1 ; G_2$,
 415 we require ways of “fusing” local types and processes. The intent is to capture in a single
 416 (sequential) specification the behavior of two distinct (sequential) specifications, i.e., those
 417 corresponding to protocols G_1 and G_2 . For local types, we have the following definition,
 418 which safely appends a local type to another:

419 ► **Definition 4.4** (Local Type Fusion). *The fusion of T_1 and T_2 , written $T_1 \circ T_2$, is given by:*

$$\begin{aligned} \mathbf{p}!\{l_i\langle U_i \rangle.T_i\}_{i \in I} \circ T &= \mathbf{p}!\{l_i\langle U_i \rangle.(T_i \circ T)\}_{i \in I} & \text{end} \circ T &= T \\ \mathbf{p}?\{l_i\langle U_i \rangle.T_i\}_{i \in I} \circ T &= \mathbf{p}?\{l_i\langle U_i \rangle.(T_i \circ T)\}_{i \in I} & (\exists \alpha.T_1) \circ T &= \exists \alpha.(T_1 \circ T) \\ (\forall \alpha.T_1) \circ T &= \forall \alpha.(T_1 \circ T) & (@_\alpha T_1) \circ T &= @_\alpha(T_1 \circ T) \\ (\downarrow \alpha.T_1) \circ T &= \downarrow \alpha.(T_1 \circ T) \end{aligned}$$

421 This way, e.g., if $T_1 = \exists \alpha.@_\alpha \mathbf{p}?\{l_1\langle \text{Int} \rangle.\text{end}, l_2\langle \text{Bool} \rangle.\text{end}\}$ and $T_2 = @_\omega \mathbf{q}!\{l\langle \text{Str} \rangle.\text{end}\}$, then
 422 $T_1 \circ T_2 = \exists \alpha.@_\alpha \mathbf{p}?\{l_1\langle \text{Int} \rangle.@_\omega \mathbf{q}!\{l\langle \text{Str} \rangle.\text{end}\}, l_2\langle \text{Bool} \rangle.@_\omega \mathbf{q}!\{l\langle \text{Str} \rangle.\text{end}\}\}$. We can now define:

423 ► **Definition 4.5** (Merge-based Projection [21]). *Let G be a global type. The merge-based
 424 projection of G under participant \mathbf{r} , denoted $G \upharpoonright \mathbf{r}$, is defined as $\text{end} \upharpoonright \mathbf{r} = \text{end}$ and*

$$\begin{aligned} \mathbf{p} \rightarrow \mathbf{q}:\{l_i\langle U_i \rangle.G_i\}_{i \in I} \upharpoonright \mathbf{r} &= \begin{cases} \mathbf{p}!\{l_i\langle U_i \rangle.G_i \upharpoonright \mathbf{r}\}_{i \in I} & \text{if } \mathbf{r} = \mathbf{p} \\ \mathbf{p}?\{l_i\langle U_i \rangle.G_i \upharpoonright \mathbf{r}\}_{i \in I} & \text{if } \mathbf{r} = \mathbf{q} \\ \sqcup_{i \in I} G_i \upharpoonright \mathbf{r} & \text{otherwise (}\sqcup \text{ as in Def. 4.3)} \end{cases} \\ (\mathbf{p} \text{ moves } \tilde{\mathbf{q}} \text{ to } \omega \text{ for } G_1 ; G_2) \upharpoonright \mathbf{r} &= \begin{cases} \downarrow \beta.(\exists \alpha.@_\alpha G_1 \upharpoonright \mathbf{r}) \circ @_\beta G_2 \upharpoonright \mathbf{r} & \text{if } \mathbf{r} = \mathbf{p} \\ \downarrow \beta.(\forall \alpha.@_\alpha G_1 \upharpoonright \mathbf{r}) \circ @_\beta G_2 \upharpoonright \mathbf{r} & \text{if } \mathbf{r} \in \tilde{\mathbf{q}} \\ G_2 \upharpoonright \mathbf{r} & \text{otherwise} \end{cases} \end{aligned}$$

427 *When no side condition holds, the map is undefined.*

428 The projection for the type \mathbf{p} moves $\tilde{\mathbf{q}}$ to ω for $G_1 ; G_2$ is one of the key points in our analysis.
 429 The local type for \mathbf{p} , the leader of the migration, starts by binding the identity of its current
 430 domain (say, $\omega_{\mathbf{p}}$) to β . Then, the (fresh) domain ω is communicated, and there is a migration
 431 step to ω , which is where protocol $G_1 \upharpoonright \mathbf{p}$ will be performed. Finally, there is a migration step
 432 from ω back to $\omega_{\mathbf{p}}$; once there, the protocol $G_2 \upharpoonright \mathbf{p}$ will be performed. The local type for all of
 433 $\mathbf{q}_i \in \tilde{\mathbf{q}}$ follows accordingly: they expect ω from \mathbf{p} ; the migration from their original domains
 434 to ω (and back) is as for \mathbf{p} . For participants in G_1 , the fusion on local types (Def. 4.4) defines
 435 a local type that includes the actions for G_1 but also for G_2 , if any: a participant in G_1 need
 436 not be involved in G_2 . Interestingly, the resulting local types $\downarrow \beta.(\exists \alpha.@_\alpha G_1 \upharpoonright \mathbf{p}) \circ @_\beta G_2 \upharpoonright \mathbf{p}$
 437 and $\downarrow \beta.(\forall \alpha.@_\alpha G_1 \upharpoonright \mathbf{q}_i) \circ @_\beta G_2 \upharpoonright \mathbf{q}_i$ define a precise combination of hybrid connectives whereby
 438 each migration step is bound by a quantifier or the current domain.

439 The following notion of *well-formedness* for global types is standard:

440 ► **Definition 4.6** (Well-Formed Global Types [32]). *We say that global type G is well-formed
 441 (WF, in the following) if the projection $G \upharpoonright \mathbf{r}$ is defined for all $\mathbf{r} \in G$.*

442 **Analyzing Global Types via Medium Processes** A *medium process* is a well-typed process
 443 from §2 that captures the communication behavior of the domain-aware global types of
 444 Def. 4.1. Here we define medium processes and establish two fundamental characterization
 445 results for them (Theorems 4.11 and 4.12). We shall consider names *indexed by participants*:
 446 given a name c and a participant \mathbf{p} , we use $c_{\mathbf{p}}$ to denote the name along which the session
 447 behavior of \mathbf{p} will be made available. This way, if $\mathbf{p} \neq \mathbf{q}$ then $c_{\mathbf{p}} \neq c_{\mathbf{q}}$. To define mediums, we
 448 need to append or fuse sequential processes, just as Def. 4.4 fuses local types:

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449 ► **Definition 4.7** (Fusion of Processes). We define \circ as the partial operator on well-typed
 450 processes such that (with $\pi \in \{c(y), c(\omega), c(\alpha), c(y@w), c(y@w), c \triangleleft l\}$) :

$$451 \quad \begin{aligned} c\langle y \rangle.([u \leftrightarrow y] \mid P) \circ Q &\triangleq c\langle y \rangle.([u \leftrightarrow y] \mid (P \circ Q)) & \mathbf{0} \circ Q &\triangleq Q \\ c \triangleright \{l_i : P_i\}_{i \in I} \circ Q &\triangleq c \triangleright \{l_i : (P_i \circ Q)\}_{i \in I} & (\pi.P) \circ Q &\triangleq \pi.(P \circ Q) \end{aligned}$$

452 and is undefined otherwise.

453 The previous definition suffices to define a medium process (or simply *medium*), which uses
 454 indexed names to uniformly capture the behavior of a global type:

455 ► **Definition 4.8** (Medium Process). Let G be a global type (cf. Def. 4.1), \tilde{c} be a set of
 456 indexed names, and $\tilde{\omega}$ a set of domains. The medium of G , denoted $M^{\tilde{\omega}}[[G]](\tilde{c})$, is defined as:

$$457 \quad \left\{ \begin{array}{ll} \mathbf{0} & \text{if } G = \text{end} \\ c_p \triangleright \{l_i : c_p(u).c_q \triangleleft l_i; \overline{c_q}(v).([u \leftrightarrow v] \mid M^{\tilde{\omega}}[[G_i]](\tilde{c}))\}_{i \in I} & \text{if } G = p \rightarrow q : \{l_i \langle U_i \rangle . G_i\}_{i \in I} \\ c_p(\alpha).c_{q_1} \langle \alpha \rangle. \dots .c_{q_n} \langle \alpha \rangle. & \text{if } G = p \text{ moves } q_1, \dots, q_n \text{ to } w \text{ for } G_1 ; G_2 \\ c_p(y_p @ \alpha).c_{q_1}(y_{q_1} @ \alpha). \dots .c_{q_n}(y_{q_n} @ \alpha). & \\ M^{\tilde{\omega}}\{\alpha/\omega_p, \dots, \alpha/\omega_{q_n}\}[[G_1]](\tilde{y}) \circ & \\ (y_p(m_p @ \omega_p).y_{q_1}(m_{q_1} @ \omega_{q_1}). \dots .y_{q_n}(m_{q_n} @ \omega_{q_n}). & \\ M^{\tilde{\omega}}[[G_2]](\tilde{m})) & \end{array} \right.$$

458 where $M^{\tilde{\omega}}[[G_1]](\tilde{c}) \circ M^{\tilde{\omega}}[[G_2]](\tilde{c})$ is as in Def. 4.7.

459 The medium for $G = p \rightarrow q : \{l_i \langle U_i \rangle . G_i\}_{i \in I}$ exploits four prefixes to mediate in the
 460 interaction between the implementations of p and q : the first two prefixes (on name c_p)
 461 capture the label selected by p and the subsequently received value; the third and fourth
 462 prefixes (on name c_q) propagate the choice and forward the value sent by p to q . We omit
 463 the forwarding and value exchange when the interaction does not involve a value payload.

464 The medium for $G = p \text{ moves } q_1, \dots, q_n \text{ to } w \text{ for } G_1 ; G_2$ showcases the expressivity and
 465 convenience of our domain-aware process framework. In this case, the medium's behavior
 466 takes place through the following steps: First, $M^{\tilde{\omega}}[[G]](\tilde{c})$ inputs a domain identifier (say, ω)
 467 from p which is forwarded to q_1, \dots, q_n , the other participants of G_1 . Secondly, the roles
 468 p, q_1, \dots, q_n migrate from their domains $\omega_p, \omega_{q_1}, \dots, \omega_{q_n}$ to ω . At this point, the medium
 469 for G_1 can execute, keeping track the current domain ω for all participants. Finally, the
 470 participants of G_1 migrate back to their original domains and the medium for G_2 executes.

471 Recalling the domain-aware global type of §1, we produce its medium process:

$$\begin{aligned} c_{c1} \triangleright \{ & \text{request} : c_{c1}(r).c_{mw} \triangleleft \text{request}; \overline{c_{mw}}(v).([r \leftrightarrow v] \mid \\ & c_{mw} \triangleright \{ \text{reply} : c_{mw}(a).c_{c1} \triangleleft \text{reply}; \overline{c_{c1}}(n).([a \leftrightarrow n] \mid c_{mw} \triangleright \{ \text{done} : c_{serv} \triangleleft \text{done}; \mathbf{0} \}), \\ & \text{wait} : c_{c1} \triangleleft \text{wait}; c_{mw} \triangleright \{ \text{init} : c_{serv} \triangleleft \text{init}; c_{mw}(w_{priv}).c_{serv}(w_{priv}). \\ & c_{mw}(y_{mw} @ w_{priv}).c_{serv}(y_{serv} @ w_{priv}).M^{w_{priv}}[[\text{Offload}]](y_{mw}, y_{serv}) \circ \\ & (y_{mw}(z_{mw} @ w_{mw}).y_{serv}(z_{serv} @ w_{serv}). \\ & z_{mw} \triangleright \{ \text{reply} : z_{mw}(a).c_{c1} \triangleleft \text{reply}; \overline{c_{c1}}(n).([a \leftrightarrow n] \mid \mathbf{0}) \} \} \} \} \} \end{aligned}$$

472 The medium ensures the client's domain remains fixed through the entire interaction,
 473 regardless of whether the middleware chooses to interact with the server. This showcases
 474 how our medium transparently manages domain migration of participants.

475 **Characterization Results** We state results that offer a sound and complete account of the
 476 relationship between: (i) a global type G (and its local types), (ii) its medium process
 477 $M^{\tilde{\omega}}[[G]](\tilde{c})$, and (iii) process implementations for the participants $\{p_1, \dots, p_n\}$ of G . In a
 478 nutshell, these results say that the typeful composition of $M^{\tilde{\omega}}[[G]](\tilde{c})$ with processes for each

479 p_1, \dots, p_n (well-typed in the system of §3) performs the intended global type. Crucially, these
 480 processes reside in distinct domains and can be independently developed, guided by their local
 481 type—they need not know about the medium’s existence or structure. The results generalize
 482 those in [7] to the domain-aware setting. Given a global type G with $\text{part}(G) = \{p_1, \dots, p_n\}$,
 483 below we write $\text{npart}(G)$ to denote the set of indexed names $\{c_{p_1}, \dots, c_{p_n}\}$. We define:

484 ► **Definition 4.9 (Compositional Typing).** *We say $\Omega; \Gamma; \Delta \vdash M^{\tilde{\omega}}[G](\tilde{c}) :: z:C$ is a composi-*
 485 *tional typing if: (i) it is a valid typing derivation; (ii) $\text{npart}(G) \subseteq \text{dom}(\Delta)$; and (iii) $C = \mathbf{1}$.*

486 A compositional typing says that $M^{\tilde{\omega}}[G](\tilde{c})$ depends on behaviors associated to each parti-
 487 cipant of G ; it also specifies that $M^{\tilde{\omega}}[G](\tilde{c})$ does not offer any behaviors of its own.

488 The following definition relates binary session types and local types: the main difference is
 489 that the former do not mention participants. Below, B ranges over base types ($\text{bool}, \text{nat}, \dots$).

490 ► **Definition 4.10 (Local Types \rightarrow Binary Types).** *Mapping $\langle\langle \cdot \rangle\rangle$ from local types T (Def. 4.1)*
 491 *into binary types A (Def. 3.1) is inductively defined as $\langle\langle \text{end} \rangle\rangle = \langle\langle B \rangle\rangle = \mathbf{1}$ and*

$$\begin{array}{lll}
 \langle\langle \mathbf{p}! \{l_i \langle U_i \rangle . T_i\}_{i \in I} \rangle\rangle & = & \oplus \{l_i : \langle\langle U_i \rangle\rangle \otimes \langle\langle T_i \rangle\rangle\}_{i \in I} \quad \langle\langle \forall \alpha . T \rangle\rangle = \forall \alpha . \langle\langle T \rangle\rangle \\
 \langle\langle \mathbf{p}^? \{l_i \langle U_i \rangle . T_i\}_{i \in I} \rangle\rangle & = & \& \{l_i : \langle\langle U_i \rangle\rangle \multimap \langle\langle T_i \rangle\rangle\}_{i \in I} \quad \langle\langle \exists \alpha . T \rangle\rangle = \exists \alpha . \langle\langle T \rangle\rangle \\
 \langle\langle @_{\omega} T \rangle\rangle & = & @_{\omega} \langle\langle T \rangle\rangle \quad \langle\langle \downarrow \alpha . T \rangle\rangle = \downarrow \alpha . \langle\langle T \rangle\rangle
 \end{array}$$

493 Our first characterization result ensures that well-formedness of a global type G guarantees
 494 the typability of its medium $M^{\tilde{\omega}}[G](\tilde{c})$ using binary session types. Hence, it ensures that
 495 multiparty protocols can be analyzed by composing the medium with independently obtained,
 496 well-typed implementations for each protocol participant. Crucially, the resulting well-typed
 497 process will inherit all correctness properties ensured by binary typability established in §3.

498 ► **Theorem 4.11 (Global Types \rightarrow Typed Mediums).** *If G is WF with $\text{part}(G) = \{p_1, \dots, p_n\}$*
 499 *then $\Omega; \Gamma; c_{p_1} : \langle\langle G \upharpoonright p_1 \rangle\rangle[\omega_1], \dots, c_{p_n} : \langle\langle G \upharpoonright p_n \rangle\rangle[\omega_n] \vdash M^{\tilde{\omega}}[G](\tilde{c}) :: z : \mathbf{1}[\omega_m]$ is a compositional*
 500 *typing, for some Ω, Γ , with $\tilde{\omega} = \omega_1, \dots, \omega_n$. We assume that $\omega_i \prec \omega_m$ for all $i \in \{1, \dots, n\}$*
 501 *(the medium’s domain is accessible by all), and that $i \neq j$ implies $\omega_i \neq \omega_j$.*

502 The second characterization result, given next, is the converse of Theorem 4.11: binary
 503 typability precisely delineates the interactions that underlie well-formed multiparty protocols.
 504 We need an auxiliary relation on local types, written $\preceq_{\downarrow}^{\perp}$, that relates types with branching
 505 and “here” type operators, which have silent process interpretations (cf. Figure 1 and [9]).
 506 First, we have $T_1 \preceq_{\downarrow}^{\perp} T_2$ if there is a T' such that $T_1 \sqcup T' = T_2$ (cf. Def. 4.3). Second,
 507 we have $T_1 \preceq_{\downarrow}^{\perp} T_2$ if (i) $T_1 = T'$ and $T_2 = \downarrow \alpha . T'$ and α does not occur in T' ; but also if
 508 (ii) $T_1 = \downarrow \alpha . T'$ and $T_2 = T' \{\omega/\alpha\}$. (See [9] for a formal definition of $\preceq_{\downarrow}^{\perp}$).

509 ► **Theorem 4.12 (Well-Typed Mediums \rightarrow Global Types).** *Let G be a global type (cf. Def. 4.1).*
 510 *If $\Omega; \Gamma; c_{p_1} : A_1[\omega_1], \dots, c_{p_n} : A_n[\omega_n] \vdash M^{\tilde{\omega}}[G](\tilde{c}) :: z : \mathbf{1}[\omega_m]$ is a compositional typing then*
 511 *$\exists T_1, \dots, T_n$ such that $G \upharpoonright p_j \preceq_{\downarrow}^{\perp} T_j$ and $\langle\langle T_j \rangle\rangle = A_j$, for all $p_j \in \text{part}(G)$.*

512 The above theorems offer a *static guarantee* that connects multiparty protocols and well-typed
 513 processes. They can be used to establish also *dynamic guarantees* relating the behavior
 514 of a global type G and that of its associated set of *multiparty systems* (i.e., the typeful
 515 composition of $M^{\tilde{\omega}}[G](\tilde{c})$ with processes for each of $p_i \in \text{part}(G)$). These dynamic guarantees
 516 can be easily obtained by combining Theorems 4.11 and 4.12 with the approach in [7].

517 **5 Related Work**

518 There is a rich history of works on the logical foundations of concurrency (see, e.g., [4, 27, 1, 3]),
 519 which has been extended to session-based concurrency by Wadler [47], Dal Lago and Di

520 Giamberardino [35], and others. Medium-based analyses of multiparty sessions were developed
521 in [7] and used in an account of multiparty sessions in an extended classical linear logic [14].

522 Two salient calculi with distributed features are the Ambient calculus [16], in which
523 processes move across *ambients* (abstractions of administrative domains), and the *distributed*
524 π -calculus (DP1) [29], which extends the π -calculus with flat locations, local communication,
525 and process migration. While domains in our model may be read as locations, this is just one
526 specific interpretation; they admit various alternative readings (e.g., administrative domains,
527 security-related levels), leveraging the partial view of the domain hierarchy. Type systems
528 for Ambient calculi such as [15, 6] enforce security and communication-oriented properties in
529 terms of ambient movement but do not cover issues of structured interaction, central in our
530 work. Garralda et al. [25] integrate binary sessions in an Ambient calculus, ensuring that
531 session protocols are undisturbed by ambient mobility. In contrast, our type system ensures
532 that both migration and communication are safe and, for the first time in such a setting,
533 satisfy global progress (i.e., session protocols never jeopardize migration and vice-versa).

534 The multiparty sessions with nested protocols of Demangeon and Honda [19] include
535 a nesting construct that is similar to our new global type \mathbf{p} moves \tilde{q} to w for $G_1 ; G_2$, which
536 also introduces nesting. The focus in [19] is on modularity in choreographic programming;
537 domains nor domain migration are not addressed. The nested protocols in [19] can have *local*
538 participants and may be parameterized on data from previous actions. We conjecture that
539 our approach can accommodate local participants in a similar way. Data parameterization
540 can be transposed to our logical setting via dependent session types [44, 46]. Asynchrony and
541 recursive behaviors can also be integrated by exploiting existing logical foundations [23, 45].

542 Balzer et al. [2] overlay a notion of world and accessibility on a system of *shared* session
543 types to ensure deadlock-freedom. Their work differs substantially from ours: they instantiate
544 accessibility as a partial-order, equip sessions with multiple worlds and are not conservative
545 wrt linear logic, being closer to partial-order-based typings for deadlock-freedom [34, 37].

546 **6** Concluding Remarks

547 We developed a Curry-Howard interpretation of hybrid linear logic as domain-aware session
548 types. Present in processes and types, domain-awareness can account for scenarios where
549 domain information is only determined at runtime. The resulting type system features strong
550 correctness properties for well-typed processes (session fidelity, global progress, termination).
551 Moreover, by leveraging a *parametric* accessibility relation, it rules out processes that
552 communicate with inaccessible domains, thus going beyond the scope of previous works.

553 As an application of our framework, we presented the first systematic study of domain-
554 awareness in a *multiparty* setting, considering multiparty sessions with domain-aware migra-
555 tion and communication whose semantics is given by a typed (binary) medium process that
556 orchestrates the multiparty protocol. Embedded in a fully distributed domain structure, our
557 medium is shown to strongly encode domain-aware multiparty sessions; it naturally allows us
558 to transpose the correctness properties of our logical development to the multiparty setting.

559 Our work opens up interesting avenues for future work. Mediums can be seen as *monitors*
560 that enforce the specification of a domain-aware multiparty session. We plan to investigate
561 contract-enforcing mediums building upon works such as [28, 33, 20], which study runtime
562 monitoring in session-based systems. Our enforcement of communication across accessible
563 domains suggests high-level similarities with information flow analyses in multiparty sessions
564 (cf. [13, 12, 17]), but does not capture the directionality needed to model such analyses
565 outright. It would be insightful to establish the precise relationship with such prior works.

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