

1 Introduction

I would like to expand this section and flesh out the examples a bit more to make them clearer.

The basic idea underpinning the game semantics for nondeterministic programming languages is to remove the constraint of *determinism* from the usual definition of a strategy (see, for example, [AJ13]) that says that the player may have at most one reply to each move made by the opponent. The determinism constraint is of little technical value and its main purpose is to provide a fully abstract denotational semantics for deterministic programming languages; if we remove it in order to study nondeterministic languages, then much of the technical apparatus of game semantics carries over immediately.

One problem that does arise, however, is that the resulting semantics no longer adequately captures the possibility of divergence in the interaction. In deterministic game semantics, divergence is represented by the absence of a reply to an opponent's move, but this is not adequate in the nondeterministic case because it gives us no way to capture a *possible* divergence. For example, if we represent divergence by the absence of a reply then Program A, which constantly returns the numeral 1, and Program B, which makes a nondeterministic choice and then either returns 1 or diverges, have the same semantics, despite exhibiting different behaviour [HM99].

We therefore need a new way to keep track of divergence. This was done by Harmer and McCusker [HM99], who resolved the problem by adding extra data to the definition of a strategy that records which opponent positions allow the possibility of divergence. Using this device, Harmer and McCusker were able to provide a fully abstract game semantics for PCF with finite nondeterminism.

There is, however, a technical subtlety that arises when we try to use the same technique to model PCF with *unbounded* nondeterminism; that is, PCF with the addition of a nondeterministic natural number generator that never diverges. Indeed, if we naively relax the Harmer-McCusker model to allow infinite branching then composition of strategies is no longer associative [Har99].

Ultimately, the reason why unbounded nondeterminism introduces problems is that it makes the language fine-grained enough to distinguish between computation that is *divergent*; i.e., a computation that carries on for infinitely many steps and does not terminate, and computation that is convergent, but may take an unbounded number of steps to do so. For example, using recursion, we may define a function that, at each step, makes a nondeterministic choice whether to call its argument or to return. If we have access to unbounded nondeterminism then we may write a function that nondeterministically chooses a natural number n , calls its argument n times and then returns. Observationally, these programs are different: the first may diverge, while the second always converges.

In the usual model of strategies as sets of positions, the strategies defined by these two programs are the same.

At first glance, it appears that the Harmer-McCusker model is fine-grained enough to distinguish these two strategies, and this is true if we define the strategies directly: the strategy denoting the first program ought to designate the opening move as divergent, whereas the strategy denoting the second program should not designate any positions as divergent. However, if we want to define these strategies compositionally, it turns out that both strategies are designated divergent, since the model treats an infinite increasing sequence of positions as a divergence occurring from livelock (the ‘infinite chattering’ in the game semantics). This inconsistency between the direct definition of the strategy and the compositional one is what leads to the failure of composition to be associative.

We need, then, some way to distinguish between computation that takes infinitely many steps and computation that takes a finite, but arbitrarily large, number of steps. One approach, taken by Tsukada and Ong [TO15] is to represent strategies as trees, rather than sets of positions; here, there is a distinction between a tree of infinite height and an infinite family of trees of finite but arbitrarily large height. We take a different approach, one suggested by the work of Roscoe and Levy ([ROS93] and [Lev08], cited in [TO15]), and by Laird’s sequential algorithms model for PCF with unbounded nondeterminism [Lai15], and enlarge our strategies to include information about the infinite positions that may occur in them.

1.1 Related Work

A more detailed overview of previous work, particularly [Lai15].

2 PCF with Countable Nondeterminism

As in [Lai15].

2.1 Type Theory

2.2 Operational Semantics

2.3 Must Testing

We are interested in soundness and adequacy for the ‘must-converge’ relation, since the ‘may-converge’ relation can be adequately modelled using finite non-determinism.

3 Game Semantics

3.1 Games

Definition 3.1. Given a set X , we write $\overline{X^*}$ for the set of all (finite and infinite) sequences of elements of X of length $\leq \omega$.

A *game* is given by a tuple

$$A = (M_A, \lambda_A, \zeta_A, P_A)$$

where

- M_A is a set of moves.
- $\lambda_A: M_A \rightarrow \{O, P\}$ designates each move as an O -move (played by Player O) or a P -move (played by Player P).
- $P_A \subseteq \overline{M_A^*}$ is a non-empty prefix-closed set of sequences of moves from M_A of length $\leq \omega$, called *positions*. We call a sequence $s \in P_A$ *infinite* if $\text{length}(s) = \omega$. Otherwise, we say that s is *finite*.
- $\zeta_A: P_A \rightarrow \{O, P\}$ designates each position in P_A as a P -position or an O -position.

The set P_A and the functions λ_A, ζ_A are required to satisfy certain additional axioms:

Compactness If $s \in M_A^\omega$ is an infinite sequence of moves such that $t \in P_A$ for all finite prefixes $t \sqsubset s$, then $s \in P_A$.

Consistency If $a \in M_A$ and $sa \in P_A$ then $\zeta_A(sa) = \lambda_A(a)$.

Alternation If $a \in M_A$ and $sa \in P_A$ then $\zeta_A(s) = \neg \zeta_A(sa)$.

Negativity $\zeta_A(\epsilon) = P$, where ϵ is the empty position.

Note that the negativity rule and the alternation rule between them imply that all starting moves are made by player O .

3.2 Strategies

Definition 3.2. Let $A = (M_A, \lambda_A, \zeta_A, P_A)$ be a game. A (nondeterministic) *strategy* for A is a pair $\sigma = (T_\sigma, D_\sigma)$, where

- T_σ is the set of *traces* of the strategy; i.e., the set of positions that can occur when player P plays according to the strategy. That is, T_σ is a non-empty prefix-closed subset of P_A that is closed under O -replies to P -positions: whenever $s \in T_\sigma$ is a P -position and $a \in M_A$ is an O -move such that $sa \in P_A$, then $sa \in T_\sigma$. We call such a set T_σ a *trace set*.

We will often identify T_σ with σ , and write $s \in \sigma$ instead of $s \in T_\sigma$.

We say that T_σ is *compact* if it satisfies the compactness criterion given above for games: if $s \in M_A^\omega$ is an infinite sequence such that $t \in T_\sigma$ for all finite prefixes $t \sqsubset s$, then $s \in T_\sigma$.

We require T_σ to satisfy the following criterion:

Local compactness For any $s \in T_\sigma$, there exists some compact trace set T_s such that $s \in T_s \subseteq T_\sigma$.

- $D_\sigma \subseteq T_\sigma$ denotes the set of *divergences* in T_σ ; that is, the set of those O -positions in T_σ for which Player P may elect to diverge rather than respond. Accordingly, $\zeta_A(s) = O$ for all $s \in D_\sigma$.

T_σ and D_σ are required to satisfy the following divergence axiom:

Diverge-or-reply If $s \in T_\sigma$ is an O -position then either $sa \in T_\sigma$ for some P -move a or there exists $t \sqsubseteq s$ such that $t \in D_\sigma$.

A consequence of the diverge-or-reply rule is that if $s \in \sigma$ is an infinite O -position, then there exists $t \sqsubseteq s$ such that $t \in D_\sigma$ (since it is impossible for player P to reply to it, positions of length $\omega + 1$ or greater being disallowed). This works well for our purposes; it captures our intuition that divergence should arise from some infinite behaviour, but it excludes those cases where Player O is ‘to blame’ for the infinite behaviour (passing, for example, a divergent function into the non-divergent strategy $\lambda f.f$).

3.3 Multiplicatives

Let A, B be games. If $s \in \overline{M_A \sqcup M_B^*}$ then we write $s|_A$ for the subsequence of s consisting of all moves from A and $s|_B$ for the subsequence of s consisting of all moves from B . We write $P_A \parallel P_B$ for the set of all such sequences s such that $s|_A \in P_A$ and $s|_B \in P_B$.

Definition 3.3. Let A, B be games. Then the *tensor product* of A and B is the game $A \otimes B = (M_{A \otimes B}, \lambda_{A \otimes B}, \zeta_{A \otimes B}, P_{A \otimes B})$ where we define $M_{A \otimes B}$, $\lambda_{A \otimes B}$, $\zeta_{A \otimes B}$, $P_{A \otimes B}$ as follows:

- $M_{A \otimes B} = M_A \sqcup M_B$
- $\lambda_{A \otimes B} = \lambda_A \sqcup \lambda_B$
- For $s \in P_A \parallel P_B$, $\zeta_{A \otimes B}(s) = \zeta_A(s|_A) \wedge \zeta_B(s|_B)$.
- $P_{A \otimes B}$ is the set of all sequences $s \in P_A \parallel P_B$ such that s satisfies the alternating condition with respect to $\zeta_{A \otimes B}$: i.e., for all $t, ta \sqsubseteq s$, $\zeta_{A \otimes B}(t) = \neg \zeta_{A \otimes B}(ta)$.

Definition 3.4. Let A, B be games. Then the *linear implication* of A and B is the game $A \multimap B = (M_{A \multimap B}, \lambda_{A \multimap B}, \zeta_{A \multimap B}, P_{A \multimap B})$ where we define $M_{A \multimap B}$, $\lambda_{A \multimap B}$, $\zeta_{A \multimap B}$, $P_{A \multimap B}$ as follows:

- $M_{A \multimap B} = M_A \sqcup M_B$
- $\lambda_{A \multimap B} = (\neg \circ \lambda_A) \sqcup \lambda_B$
- For $s \in P_A \parallel P_B$, $\zeta_{A \multimap B}(s) = \zeta_A(s|_A) \wedge \zeta_B(s|_B)$.
- $P_{A \multimap B}$ is the set of all sequences $s \in P_A \parallel P_B$ such that s satisfies the alternating condition with respect to $\zeta_{A \multimap B}$.

We want to prove that these are well formed games.

Proposition 3.5. *If A, B are games then $A \otimes B$ and $A \multimap B$ are games.*

First, we will prove a useful lemma.

Lemma 3.6. *Let A, B be games. Given a position $s \in P_A \parallel P_B$, we define the sign profile of s to be given by the signs of its two components:*

$\zeta_A(s _A)$	$\zeta_B(s _B)$	sign profile
P	P	PP
O	P	OP
P	O	PO
O	O	OO

If $s \in P_{A \otimes B}$ is a finite position, then s cannot have sign profile OO . If $s \in P_{A \multimap B}$ is a finite position then s cannot have sign profile OP .

Proof. By negativity, the empty sequence ϵ always has sign profile PP . Otherwise, $s = s'a$ for some sequence s' and some move a . If $s \in P_{A \otimes B}$ and s has sign profile OO , then s is an O -position in $A \otimes B$. Therefore, s' is a P -position in $A \otimes B$ and so s' must have sign profile PP , by the definition of $\zeta_{A \otimes B}$. But this is impossible, as the move a can only change the sign profile in one of the two components.

The proof for the linear implication is entirely similar. \square

Proof of Proposition 3.5. Alternation is part of the definition and negativity is implied by the equations $P \wedge P = P$ and $P \Rightarrow P = P$. The only tricky part is proving consistency of the λ and ζ functions. Since consistency applies only to positions with a last move, we may ignore the infinite plays in A and B .

Suppose $sa \in P_{A \otimes B}$. We wish to show that $\zeta_A(sa) = \lambda_A(a)$. In the presence of alternation, this is equivalent to showing that $\zeta_A(s) = \neg \lambda_A(a)$. We show this by cases on the sign profile of s . By Lemma 3.6, s has sign profile PP , OP or PO . If s has sign profile PP then s is a P -position. Since $s|_A$ and $s|_B$ are both P -positions, a must be an O -move, whether it occurs in A or B .

If instead s has sign profile OP or PO , then s is an O -position. By alternation, sa must be a P -position, so it must have sign profile PP . By consistency and alternation for the games A, B , the move a must be a P -move.

For compactness, suppose that $s \in M_{A \otimes B}^\omega$ is an infinite sequence of moves such that $t \in P_{A \otimes B}$ for all finite prefixes $t \sqsubset s$. Then s is certainly alternating. Moreover, for all finite prefixes $t \sqsubset s|_A$, we have $t \in P_A$, and so therefore $s|_A \in P_A$ by compactness for A . Similarly, $s|_B \in P_B$, and therefore, $s \in P_{A \otimes B}$.

The proof for the linear implication is similar. \square

Looking at the proof above, we may deduce the following important fact:

Proposition 3.7. *In the tensor product $A \otimes B$, only player O may switch games. In the linear implication $A \multimap B$, only player P may switch games.*

3.4 Composition of Strategies

Let A, B, C be games, let σ be a strategy for $A \multimap B$ and let τ be a strategy for $B \multimap C$. We shall construct a strategy $\tau \circ \sigma$ for $A \multimap C$.

In order to define $T_{\tau \circ \sigma}$, we first define the set $\sigma \parallel \tau$, given by:

$$\sigma \parallel \tau = \left\{ \mathfrak{s} \in \overline{(M_A \sqcup M_B \sqcup M_C)^*} : \mathfrak{s}|_{A,B} \in \sigma, \mathfrak{s}|_{B,C} \in \tau \right\}$$

We then define

$$T_{\tau \circ \sigma} = \{ \mathfrak{s}|_{A,C} : \mathfrak{s} \in \sigma \parallel \tau \}$$

We need to prove that $T_{\tau \circ \sigma} \subseteq P_{A \multimap C}$. If $\mathfrak{s} \in \sigma \parallel \tau$, then $\mathfrak{s}|_{A,C}|_A = \mathfrak{s}|_A = \mathfrak{s}|_{A,B}|_A \in P_A$, and similarly $\mathfrak{s}|_{A,C} \in P_C$, so certainly $\mathfrak{s}|_{A,C} \in P_A \parallel P_C$. It will suffice, then, to show that $\mathfrak{s}|_{A,C}$ is alternating with respect to $\zeta_{A \multimap C}$.

Proposition 3.8. *Let A, B, C be games, let σ be a strategy for $A \multimap B$ and let τ be a strategy for $B \multimap C$. Suppose $s, sa \in \tau \circ \sigma$. Then $\zeta_{A \multimap C}(s) = \neg \lambda_{A \multimap C}(a)$.*

Proof. Write $sa = \mathfrak{s}a|_{A,C}$, where $\mathfrak{s}a \in \sigma \parallel \tau$. Then $\mathfrak{s}|_{A,C} = s$. s, sa must be finite, so, by Lemma 3.6, neither $\mathfrak{s}|_{A,B}$ nor $\mathfrak{s}|_{B,C}$ may have sign profile OP , so we get four possible sign profiles for \mathfrak{s} giving us the following values for $\zeta_{A \multimap C}(\mathfrak{s}|_{A,C})$:

$\zeta_A(\mathfrak{s} _A)$	$\zeta_B(\mathfrak{s} _B)$	$\zeta_C(\mathfrak{s} _C)$	$\zeta_{A \multimap C}(s _{A,C})$
P	P	P	P
P	P	O	O
P	O	O	O
O	O	O	P

Suppose that a is an O -move in $A \multimap C$: so a is a P -move in A or an O -move in C . By alternation in the component games, playing the move a either turns an O -position in A into a P -position in A or turns a P -position in C into an

O -position in C . That is, we must be switching from sign profile PPP to sign profile PPO or from sign profile OOO to sign profile POO . In either case, $s = \mathfrak{s}|_{A,C}$ must be a P -position.

Similarly, if a is a P -move in $A \multimap C$, then switching from \mathfrak{s} to $\mathfrak{s}a$ must move us from sign profile PPO to sign profile PPP or from sign profile POO to sign profile OOO ; in either case, s must be an O -position. \square

To complete the proof that $T_{\tau \circ \sigma}$ is a legal trace set for a strategy, we need to show that $T_{\tau \circ \sigma}$ is closed under opponent replies and that it is locally compact.

Proposition 3.9. *Let A, B, C be games, let σ be a strategy for $A \multimap B$ and let τ be a strategy for $B \multimap C$. Suppose $s \in \tau \circ \sigma$ is a P -position such that $sa \in P_{A \multimap C}$ for some O -move a . Then $sa \in \tau \circ \sigma$.*

Proof. Write $s = \mathfrak{s}|_{A,C}$, for $\mathfrak{s} \in \sigma \parallel \tau$. We show that $\mathfrak{s}a \in \sigma \parallel \tau$: so $sa = \mathfrak{s}a|_{A,C} \in \tau \circ \sigma$.

Since s is a P -position, the sign profile of \mathfrak{s} must be PPP or OOO . It follows that $\mathfrak{s}|_{A,B} \in \sigma$ and $\mathfrak{s}|_{B,C} \in \tau$ are both P -positions. Since a is a P -move in $A \multimap C$, it must be either a P -move in $A \multimap B$ or a P -move in $B \multimap C$, by straightforward analysis of the definitions of the λ functions. It follows that either $s|_{A,B}a \in \sigma$ (if a is a move in A) or that $s|_{B,C}a \in \tau$ (if a is a move in C). In either case, we have $\mathfrak{s}a \in \sigma \parallel \tau$, as desired. \square

Proposition 3.10. *Let A, B, C be games, let σ be a strategy for $A \multimap B$ and let τ be a strategy for $B \multimap C$. Then $\tau \circ \sigma$ is locally compact.*

In order to prove that the composition of locally compact strategies is locally compact, we are going to need some facts about deterministic strategies.

Definition 3.11. We say a strategy σ is *deterministic* if whenever $s \in \sigma$ is an O -position and a, b are moves such that $sa, sb \in \sigma$, then $a = b$.

Deterministic strategies have the following nice technical property:

Proposition 3.12. *Let A, B, C be games, let σ be a deterministic strategy for $A \multimap B$ and let τ be a deterministic strategy for $B \multimap C$. Then $\tau \circ \sigma$ is a deterministic strategy. Moreover, for any $s \in \tau \circ \sigma$, there is a unique minimal $\mathfrak{s} \in \sigma \parallel \tau$ such that $\mathfrak{s}|_{A,C} = s$.*

Proof. The idea behind the proof is that determinism of σ and τ mean that the play in the intermediate game B is completely determined (since every move played in B is either a P -move in $A \multimap B$ or a P -move in $B \multimap C$). For full details, see [AJ13]. \square

We can use this to prove the following:

Proposition 3.13. *Let A, B, C be games and let $\sigma: A \multimap B$ and $\tau: B \multimap C$ be compact deterministic strategies. Then $\tau \circ \sigma$ is compact.*

Proof. Let $s \in M_{A \multimap C}^\omega$ be an infinite sequence such that $t \in \tau \circ \sigma$ for all finite prefixes $t \sqsubset s$. For each finite prefix t of s , there is a unique minimal sequence $\mathbf{t} \in \sigma \parallel \tau$ such that $\mathbf{t}|_{A,C} = t$. Writing s as the limit of its finite prefixes

$$t_1 \sqsubseteq t_2 \sqsubseteq t_3 \sqsubseteq \dots$$

we build up a sequence

$$\mathbf{t}_1 \sqsubseteq \mathbf{t}_2 \sqsubseteq \mathbf{t}_3 \sqsubseteq \dots$$

where \mathbf{t}_i is the unique minimal sequence in $\sigma \parallel \tau$ such that $\mathbf{t}_i|_{A,C} = t_i$. We have $\mathbf{t}_i \sqsubseteq \mathbf{t}_{i+1}$ because if we remove the last move from \mathbf{t}_{i+1} then the resulting sequence \mathbf{u}_i satisfies $\mathbf{u}_i|_{A,C} = t_i$ and therefore $\mathbf{t}_i \sqsubseteq \mathbf{u}_i \sqsubseteq \mathbf{t}_{i+1}$ by minimality of \mathbf{t}_i .

Then the limit of the sequences $\mathbf{t}_i|_{A,B}$ must be contained in σ , since σ is compact, and similarly the limit of the sequences $\mathbf{t}_i|_{B,C}$ must be contained in τ , since τ is compact. It follows that the limit \mathbf{t} of the sequences \mathbf{t}_i is contained in $\sigma \parallel \tau$, and therefore that $\mathbf{t}|_{A,C} = s \in \tau \circ \sigma$. \square

Note that the limit of compact nondeterministic strategies need not be compact.

Example 3.14. Let the games I and Σ^* be defined as before, and let the game Σ be the game with a unique opponent starting move and a unique player reply:

$$\Sigma = (\{q, a\}, \{q \mapsto o, a \mapsto p\}, \{\epsilon \mapsto p, q \mapsto o, qa \mapsto p\}, \{\epsilon, q, qa\})$$

Let \mathbb{N} be the game where the opponent asks the player to choose a natural number:

$$\mathbb{N} = (\{q\} \cup \mathbb{N}, \{q \mapsto O, n \mapsto P\}, \{\epsilon \mapsto P, q \mapsto O, qn \mapsto P\}, \{\epsilon, q\} \cup \{qn : n \in \mathbb{N}\})$$

We have a (deterministic) strategy σ for $\mathbb{N} \multimap (\Sigma^* \multimap \Sigma)$ in which the player asks the opponent for a number n and then calls the argument of Σ^* n times before returning. For example, a play in σ might look like this:

$$\begin{array}{ccccc} \mathbb{N} & \Sigma^* & \Sigma & & \\ & & q & & \\ & q & & & \\ & 2 & & & \\ & & q & & \\ & & a & & \\ & & q & & \\ & & a & & \\ & & & & a \end{array}$$

σ is compact because there are no infinite chains of positions; indeed, the length of a play in σ is already determined by the third move.

We have a nondeterministic strategy $?$ for $\mathbb{N} \cong I \multimap \mathbb{N}$ where the player nondeterministically chooses any number - so $? = P_{\mathbb{N}}$ as sets of positions. $?$ is compact because all plays in $?$ have length at most 2.

When we compose these strategies, the resulting strategy $\sigma \circ \tau$ contains the infinite chain of positions $q, qqa, qqqa, qqqaqa, \dots$, but does not contain any limiting plays. So it is not compact. It is, however, locally compact, since it is the union of compact strategies σ_n , where σ_n has the unique maximal play

$$\underbrace{qqa \dots qqa}_{n \text{ times}}$$

Proposition 3.15. *Let A, B, C be games and let $\sigma: A \multimap B$ and $\tau: B \multimap C$ be (nondeterministic, locally compact) strategies. Then $\tau \circ \sigma$ is locally compact.*

Proof. Let $s \in T_{\tau \circ \sigma}$. Then there is some sequence $\mathfrak{s} \in \sigma \parallel \tau$ such that $\mathfrak{s}|_{A,C} = s$. We have $\mathfrak{s}|_{A,B} \in \sigma$ and $\mathfrak{s}|_{B,C} \in \tau$, so, by local compactness for σ and τ , there are compact strategies $\sigma': A \multimap B$ and $\tau': B \multimap C$ such that $\mathfrak{s}|_{A,B} \in \sigma'$ and $\mathfrak{s}|_{B,C} \in \tau'$. After removing positions from σ' and τ' , we may assume that they are deterministic (and still compact). Then $\tau' \circ \sigma'$ is compact and we have $\mathfrak{s}|_{A,C} \in \tau' \circ \sigma' \subseteq \tau \circ \sigma$. \square

Before we consider the definition of $D_{\tau \circ \sigma}$, we show that composition is associative at the level of trace sets.

Proposition 3.16. *Let A, B, C be games, let σ be a strategy for $A \multimap B$, let τ be a strategy for $B \multimap C$ and let v be a strategy for $C \multimap D$. Then*

$$T_{v \circ (\tau \circ \sigma)} = T_{(v \circ \tau) \circ \sigma}$$

Proof. As in [AJ13]. Define

$$\sigma \parallel \tau \parallel v = \left\{ \mathfrak{s} \in \overline{(M_A \sqcup M_B \sqcup M_C \sqcup M_D)^*} : \mathfrak{s}|_{A,B} \in \sigma, \mathfrak{s}|_{B,C} \in \tau, \mathfrak{s}|_{C,D} \in v \right\}$$

We shall show that

$$T_{v \circ (\tau \circ \sigma)} = \{ \mathfrak{s}|_{A,D} : \mathfrak{s} \in \sigma \parallel \tau \parallel v \}$$

The same claim will follow for $T_{(v \circ \tau) \circ \sigma}$ by symmetry, completing the proof.

Let $\mathfrak{s} \in \sigma \parallel \tau \parallel v$. Then $\mathfrak{s}|_{A,B,C} \in \sigma \parallel \tau$ and so $\mathfrak{s}|_{A,C} \in \tau \circ \sigma$. Now we see that $\mathfrak{s}|_{A,C,D} \in (\tau \circ \sigma) \parallel v$ and so $\mathfrak{s}|_{A,D} \in v \circ (\tau \circ \sigma)$. We have shown that

$$\{ \mathfrak{s}|_{A,D} : \mathfrak{s} \in \sigma \parallel \tau \parallel v \} \subseteq T_{v \circ (\tau \circ \sigma)}$$

To show the reverse inclusion, suppose that $s \in v \circ (\tau \circ \sigma)$. Let $\mathfrak{s} \in (\tau \circ \sigma) \parallel v$ be such that $\mathfrak{s}|_{A,D} = s$ and let $\mathfrak{t} \in \sigma \parallel \tau$ be such that $\mathfrak{t}|_{A,C} = \mathfrak{s}|_{A,C}$. Our goal is to interleave the sequences \mathfrak{s} and \mathfrak{t} in order to give rise to a sequence $\mathfrak{u} \in \sigma \parallel \tau \parallel v$ such that $\mathfrak{u}|_{A,D} = s$.

Note that since $\mathfrak{s}|_{A,C} = \mathfrak{t}|_{A,C}$, we may decompose \mathfrak{s} and \mathfrak{t} into blocks:

$$\begin{aligned} \mathfrak{s} &= \mathfrak{s}_0 D_0 \mathfrak{s}_1 D_1 \dots \\ \mathfrak{t} &= \mathfrak{s}_0 B_0 \mathfrak{s}_1 B_1 \dots \end{aligned}$$

where $\mathfrak{s}_1, \mathfrak{s}_2, \dots$ are sequences of moves from either A or C , $B_0, B_1 \dots$ are (possibly empty) sequences of moves from B and D_0, D_1, \dots are (possibly empty) sequences of moves from D .

We then form the sequence \mathfrak{u} as:

$$\mathfrak{u} = \mathfrak{s}_0 B_0 D_0 \mathfrak{s}_1 B_1 D_1 \dots$$

It might look as if we have made an arbitrary choice in placing the B_i before the D_i , but in fact it turns out that there is no choice to make: an examination of sign profiles, for example, will show that B_i is non-empty only if D_i is empty and vice versa: if \mathfrak{s}_i can be followed by a move from B then it cannot be followed by a move from D .

In any case, we have

$$\begin{aligned} \mathfrak{u}|_{A,C,D} &= \mathfrak{s}_0 D_0 \mathfrak{s}_1 D_1 \dots = \mathfrak{s} \\ \mathfrak{u}|_{A,B,C} &= \mathfrak{s}_0 B_0 \mathfrak{s}_1 B_1 \dots = \mathfrak{t} \end{aligned}$$

It follows that $\mathfrak{u} \in \sigma \parallel \tau \parallel \nu$:

$$\begin{aligned} \mathfrak{u}|_{A,B} &= \mathfrak{t}|_{A,B} \in \sigma \\ \mathfrak{u}|_{B,C} &= \mathfrak{t}|_{B,C} \in \tau \\ \mathfrak{u}|_{C,D} &= \mathfrak{s}|_{C,D} \in \nu \end{aligned}$$

Lastly, we have $\mathfrak{u}|_{A,D} = \mathfrak{s}|_{A,D} = s$, completing the proof. \square

At the moment, we have an associative composition at the level of trace sets. We now define composition at the level of divergences.

Definition 3.17. Let A, B, C be games, let σ be a strategy for $A \multimap B$ and let τ be a strategy for $B \multimap C$. We define the divergences of $\tau \circ \sigma$ as follows:

$$D_{\tau \circ \sigma} = \{\mathfrak{s}|_{A,C} : \mathfrak{s} \in \sigma \parallel \tau \text{ and either } \mathfrak{s}|_{A,B} \in D_\sigma \text{ or } \mathfrak{s}|_{B,C} \in D_\tau\}$$

Remark 3.18. Since D_σ and D_τ consist of O -positions, any $\mathfrak{s} \in \sigma \parallel \tau$ such that $\mathfrak{s}|_{A,B} \in D_\sigma$ or $\mathfrak{s}|_{B,C} \in D_\tau$ must have sign profile POO or PPO , by Lemma 3.6, and therefore $\mathfrak{s}|_{A,C}$ must be an O -position. It follows that $D_{\tau \circ \sigma}$ consists of O -positions.

Unlike [HM99], we do not need to change the definition of $D_{\tau \circ \sigma}$ to reflect divergence arising from infinite chattering. The following example shows that it arises naturally from existing definition of $D_{\tau \circ \sigma}$.

Example 3.19 (Infinite chattering). Let Σ^* denote the game where each player has exactly one move available in every position and the resulting infinite position is a P -position:

$$\Sigma^* = (\{q, a\}, \{q \mapsto O, a \mapsto P\}, \{\epsilon \mapsto P, sq \mapsto O, sa \mapsto P, qaqa \dots \mapsto P\}, \{s \sqsubseteq qaqa \dots\})$$

Let I denote the empty game with no moves, and let \perp denote the game with a single opponent move and no player reply:

$$\begin{aligned} I &= (\emptyset, \emptyset, \{\epsilon \mapsto P\}, \{\epsilon\}) \\ \perp &= (\{\ast\}, \{\ast \mapsto O\}, \{\epsilon \mapsto P, \ast \mapsto O\}, \{\epsilon, \ast\}) \end{aligned}$$

There are natural strategies σ for $I \multimap \Sigma^\ast$ and τ for $\Sigma^\ast \multimap \perp$ given at the level of traces by:

$$\begin{aligned} \sigma &= \{s \sqsubseteq qaqa \dots\} \\ \tau &= \{s \sqsubseteq \ast qaqa \dots\} \end{aligned}$$

Player P always has a reply to an O -position in σ , and we set $D_\sigma = \emptyset$. In τ , the infinite sequence $\ast qaqa \dots$ satisfies $\zeta_{\Sigma^\ast}(\ast qaqa \dots |_{\Sigma^\ast}) = \zeta_{\Sigma^\ast}(qaqa \dots) = P$ and $\zeta_\perp(\ast qaqa \dots |_\perp) = \zeta_\perp(\ast) = O$ and so it is an O -position. As in the remark at the end of the definition of a strategy, this O -position can have no P -reply, so it (or some prefix) must be designated divergent. We set

$$D_\tau = \{\ast qaqa \dots\}$$

Now, when we compose the strategies σ and τ , at the level of traces we have

$$\tau \circ \sigma = \{\epsilon, \ast\}$$

The sequence \ast is the restriction to I, \perp of the infinite sequence

$$\ast qaqa \dots \in \sigma \parallel \tau$$

We now have that $\ast qaqa \dots |_{\Sigma^\ast, \perp} \in D_\tau$ and therefore the sequence $\ast \in \tau \circ \sigma$ must be designated divergent. We have

$$D_{\tau \circ \sigma} = \{\ast\}$$

as desired.

Note that if we modify the definition of Σ^\ast so that the infinite position is an O -position, then we still get a divergence – this time, because the sequence $\ast qaqa \dots |_{I, \sigma^\ast}$ must be contained in D_σ . If we leave out the infinite position from σ or τ altogether, then that strategy is no longer locally compact, so it is not a valid strategy according to our definition.

This example is at the heart of the proof that the composition of strategies satisfies the diverge-or-reply rule. This is the point at which we need local compactness.

Proposition 3.20. *Let A, B, C be games, let σ be a strategy for $A \multimap B$ and let τ be a strategy for $B \multimap C$. Then $D_{\tau \circ \sigma}$ satisfies the diverge-or-reply rule.*

Proof. Suppose that $s \in \tau \circ \sigma$ is an O -position and that $s \notin D_{\tau \circ \sigma}$. Let $\mathfrak{s} \in \sigma \parallel \tau$ be such that $\mathfrak{s}|_{A,C} = s$. By local compactness of σ and τ , there must be compact strategies $\sigma' : A \multimap B$ and $\tau' : B \multimap C$ such that $\mathfrak{s}|_{A,C} \in \sigma'$ and $\mathfrak{s}|_{B,C} \in \tau'$.

Let $\mathfrak{s}' \in \sigma' \parallel \tau'$ be maximal such that $\mathfrak{s}'|_{A,C} = s$. We know that such a maximal sequence must exist: if \mathfrak{s}_i are a chain of sequences from $\sigma' \parallel \tau'$ such that $\mathfrak{s}_i|_{A,C} = s$ then their limit \mathfrak{s} (which is contained in $\sigma' \parallel \tau'$ by compactness of σ' and τ') must satisfy $\mathfrak{s}|_{A,C} = \mathfrak{s}$. Since $s \notin D_{\tau \circ \sigma}$, we must have $\mathfrak{s}|_{A,B} \notin D_\sigma$ and $\mathfrak{s}|_{B,C} \notin D_\tau$.

Since s is an O -position, one of $\mathfrak{s}|_{A,B}$ and $\mathfrak{s}|_{B,C}$ must be an O -position (by transitivity of \Rightarrow). Suppose without loss of generality that $\mathfrak{s}|_{A,B}$ is an O -position. Since $\mathfrak{s}|_{A,B} \notin D_\sigma$, there must be some move x such that $\mathfrak{s}|_{A,B}x \in \sigma$, since σ satisfies the diverge-or-reply rule. Then we have $\mathfrak{s}x|_{A,B} \in \sigma$. Moreover, Lemma 3.6 tells us that $\mathfrak{s}|_{B,C}$ must be a P -position, so $\mathfrak{s}x|_{B,C} \in \tau$, since τ is closed under opponent replies. Therefore, $\mathfrak{s}x \in \sigma \parallel \tau$. By maximality of \mathfrak{s} , x must be a move in A and therefore we have $\mathfrak{s}x \in \sigma \circ \tau$. \square

We now have a working definition of composition. It remains to prove that it is associative at the level of divergences:

Proposition 3.21. *Let A, B, C, D be games, let σ be a strategy for $A \multimap B$, let τ be a strategy for $B \multimap C$ and let v be a strategy for $C \multimap D$. Then*

$$D_{v \circ (\tau \circ \sigma)} = D_{(v \circ \tau) \circ \sigma}$$

Proof. We claim that

$$D_{v \circ (\tau \circ \sigma)} = \{\mathfrak{s}|_{A,D} : \mathfrak{s} \in \sigma \parallel \tau \parallel v \text{ and either } \mathfrak{s}|_{A,B} \in D_\sigma \text{ or } \mathfrak{s}|_{B,C} \in D_\tau \text{ or } \mathfrak{s}|_{C,D} \in D_v\}$$

The same claim will hold for $D_{(v \circ \tau) \circ \sigma}$ by symmetry, completing the proof.

Let $\mathfrak{s} \in \sigma \parallel \tau \parallel v$ be such that either $\mathfrak{s}|_{A,B} \in D_\sigma$ or $\mathfrak{s}|_{B,C} \in D_\tau$ or $\mathfrak{s}|_{C,D} \in D_v$. Then either $\mathfrak{s}|_{A,C} \in D_{\tau \circ \sigma}$ or $\mathfrak{s}|_{B,C} \in D_v$ and therefore $\mathfrak{s}|_{A,D} \in D_{v \circ (\tau \circ \sigma)}$.

Conversely, suppose that $s \in D_{v \circ (\tau \circ \sigma)}$. By the definition of $D_{v \circ (\tau \circ \sigma)}$, there must be some sequence $\mathfrak{s} \in (\tau \circ \sigma) \parallel v$ such that $\mathfrak{s}|_{A,D} = s$ and either $\mathfrak{s}|_{A,C} \in D_{\tau \circ \sigma}$ or $\mathfrak{s}|_{C,D} \in D_v$.

We now know that there is a sequence $\mathfrak{t} \in \sigma \parallel \tau$ such that $\mathfrak{t}|_{A,C} = \mathfrak{s}|_{A,C}$. If $\mathfrak{s}|_{A,C} \in D_{\tau \circ \sigma}$ then either $\mathfrak{t}|_{A,B} \in D_\sigma$ or $\mathfrak{t}|_{B,C} \in D_\tau$.

We now have the sequences \mathfrak{s} and \mathfrak{t} and we know that either $\mathfrak{t}|_{A,B} \in D_\sigma$ or $\mathfrak{t}|_{B,C} \in D_\tau$ or $\mathfrak{s}|_{C,D} \in D_v$. By the proof of Proposition 3.16, we are able to interleave the sequences \mathfrak{s} and \mathfrak{t} to get a sequence $\mathfrak{u} \in \sigma \parallel \tau \parallel v$ such that $\mathfrak{u}|_{A,C,D} = \mathfrak{s}$ and $\mathfrak{u}|_{A,B,C} = \mathfrak{t}$. Now we have either $\mathfrak{u}|_{A,B} = \mathfrak{t}|_{A,B} \in D_\sigma$ or $\mathfrak{u}|_{B,C} = \mathfrak{t}|_{B,C} \in D_\tau$ or $\mathfrak{u}|_{C,D} = \mathfrak{s}|_{C,D} \in D_v$. Moreover, $\mathfrak{u}|_{A,D} = \mathfrak{s}|_{A,D} = s$ and therefore s is contained in the set on the right, which completes the proof. \square

In order to show that we have a category, it remains to define the identity morphisms. These are given by the usual copycat strategies:

$$\text{id}_A = \{s \in P_{A_1 \multimap A_2} : \text{for all even length } t \sqsubseteq s, t|_{A_1} = t|_{A_2}\}$$

(Here, we consider infinite plays to have even length).

The divergence set D_{id_A} is empty: note that infinite positions in id_A are always P -positions.

Theorem 3.22. *There is a category \mathcal{G} where the objects are games as defined above, morphisms from a game A to a game B are given by nondeterministic strategies (T_σ, D_σ) for $A \multimap B$ and the composition and identity morphisms are as defined above.*

Proof. All that is left to do is to show that id_A really is an identity morphism. We shall show that if A and B are games and σ is a strategy for $A \multimap B$ then $\sigma \circ \text{id}_A = \sigma$; it will follow by a symmetrical argument that $\text{id}_B \circ \sigma = \sigma$.

We first show that $T_{\sigma \circ \text{id}_A} = T_\sigma$. Because of closure under opponent replies, it suffices to show that σ and $\sigma \circ \text{id}_A$ contain the same P -positions. If s is a P -position in $\sigma \circ \text{id}_A$, then there is some sequence $\mathfrak{s} \in \text{id}_A \parallel \sigma$ such that $\mathfrak{s}|_{A_1, B} = s$. Since $\mathfrak{s}|_{A_1, B}$ is a P -position, it must have sign profile PPP or OOO by Lemma 3.6, and therefore $\mathfrak{s}|_{A_1, A_2}$ is a P -position, so has even length. Therefore, $\mathfrak{s}|_{A_1} = \mathfrak{s}|_{A_2}$ and so $s = \mathfrak{s}|_{A_1, B} = \mathfrak{s}|_{A_2, B} \in \sigma$.

Conversely, suppose that $s \in \sigma$ is a P -position. There is an obvious sequence $s^2 \in \text{id}_A$, given by copying the moves of $s|_A$ between copies of A , such that $s^2|_{A_1} = s^2|_{A_2} = s|_A$. Then $s^2|_{A_2} = s|_{A_2}$, and so the sequences s^2 and s may be interleaved as in the proof of Proposition 3.16 to yield a sequence $\mathfrak{s} \in \text{id}_A \parallel \sigma$ such that $\mathfrak{s}|_{A_1, B} = \mathfrak{s}|_{A_2, B} = s$.

Now we show that $D_{\sigma \circ \text{id}_A} = D_\sigma$. Suppose $s \in D_{\sigma \circ \text{id}_A}$. Then there is a sequence $\mathfrak{s} \in \text{id}_A \parallel \sigma$ such that $\mathfrak{s}|_{A_1, B} = s$ and either $\mathfrak{s}|_{A_1, A_2} \in D_{\text{id}_A}$ or $\mathfrak{s}|_{A_2, B} \in D_\sigma$. Since $D_{\text{id}_A} = \emptyset$, we must have $\mathfrak{s}|_{A_2, B} \in D_\sigma$. In particular, $\mathfrak{s}|_{A_2, B}$ is an O -position in $A \multimap B$ and so $\mathfrak{s}|_{A_2}$ is a P -position in A . It follows by Lemma 3.6 that $\mathfrak{s}|_{A_1, A_2}$ is a P -position in $A \multimap A$; hence, it is even-length and so $\mathfrak{s}|_{A_1} = \mathfrak{s}|_{A_2}$. It follows that $s = \mathfrak{s}|_{A_1, B} = \mathfrak{s}|_{A_2, B} \in D_\sigma$. So $D_{\sigma \circ \text{id}_A} \subseteq D_\sigma$.

Conversely, suppose that $s \in D_\sigma$. We know already that there is some $\mathfrak{s} \in \text{id}_A \parallel \sigma$ such that $\mathfrak{s}|_{A_1, A_2} \in \text{id}_A$ and $\mathfrak{s}|_{A_2, B} \in \sigma$. Then $\mathfrak{s}|_{A, C} \in D_{\sigma \circ \text{id}_A}$ by definition. \square

3.5 Symmetric monoidal closed structure

We make the category \mathcal{G} into a symmetric monoidal closed category with tensor product given by \otimes and linear implication given by \multimap . At the level of morphisms, the action of $_ \otimes _$ is defined as follows: if A, B, C, D are games, σ is a strategy for $A \multimap C$ and τ is a strategy for $B \multimap D$, then $\sigma \otimes \tau$ is the strategy

for $(A \otimes B) \multimap (C \otimes D)$ given by playing the strategy σ in A and C and playing the strategy τ in B and D :

$$\sigma \otimes \tau = \{s \in P_{(A \otimes B) \multimap (C \otimes D)} : s|_{A,C} \in \sigma, s|_{B,D} \in \tau\}$$

The divergences for $\sigma \otimes \tau$ are defined using the divergences for σ and τ :

$$D_{\sigma \otimes \tau} = \{s \in P_{(A \otimes B) \multimap (C \otimes D)} : s|_{A,C} \in D_\sigma, s|_{B,D} \in D_\tau\}$$

Proposition 3.23. $\sigma \otimes \tau$ is a valid strategy for $(A \otimes B) \multimap (C \otimes D)$

Proof. $\sigma \otimes \tau$ is non-empty and prefix-closed, since σ and τ are. To show that it is a valid trace-set, we need to show that it is closed under opponent replies.

Let $s \in \sigma \otimes \tau$ be a P -position and suppose that $sx \in P_{(A \otimes B) \multimap (C \otimes D)}$ for some move x . We start with some brief analysis of sign profiles.

By Lemma 3.6, $s|_{A,B}$ and $s|_{C,D}$ must either both be O -positions or both be P -positions. If they are P -positions, then the only possibility for the sign profile of s is:

$$\frac{\zeta_A(s|_A) \quad \zeta_B(s|_B) \quad \zeta_C(s|_C) \quad \zeta_D(s|_D)}{P \quad P \quad P \quad P}$$

Otherwise, if they are both O -positions, then each of $s|_{A,B}$ and $s|_{C,D}$ may either have sign profile OP or sign profile PO , by Lemma 3.6. But now, since $s|_{A,C} \in \sigma \subseteq P_{A \multimap C}$ and since $s|_{B,D} \in \tau \subseteq P_{B \multimap D}$, we also see that neither $s|_{A,C}$ nor $s|_{B,D}$ may have sign profile OP . We therefore have two more possibilities for the sign profile of s :

$$\frac{\zeta_A(s|_A) \quad \zeta_B(s|_B) \quad \zeta_C(s|_C) \quad \zeta_D(s|_D)}{P \quad O \quad P \quad O}$$

$$O \quad P \quad O \quad P$$

In all three cases, $s|_{A,C}$ and $s|_{B,D}$ are both P -positions. Since σ and τ are both closed under opponent replies, it follows that one of them must contain the move x as a reply to the current position, and therefore that $sx \in \sigma \otimes \tau$, as desired.

Now we need to show that $\sigma \otimes \tau$ is locally compact. We first show that if σ and τ are compact strategies then $\sigma \otimes \tau$ is compact. Indeed, suppose that $s \in \sigma \otimes \tau$ is an infinite sequence such that $t \in \sigma \otimes \tau$ for all finite prefixes $t \sqsubset s$. Then σ must contain all finite prefixes of $s|_{A,C}$, so it must contain $s|_{A,C}$, since σ is compact. Similarly, τ must contain $s|_{B,D}$. Therefore, $s \in \sigma \otimes \tau$. Since s was arbitrary, it follows that $\sigma \otimes \tau$ is compact.

Now suppose that σ and τ are locally compact. Let $s \in \sigma \otimes \tau$. Then there exists compact strategies $\sigma': A \multimap C$ and $\tau': B \multimap D$ such that $s|_{A,C} \in \sigma'$ and $s|_{B,D} \in \tau'$. Then $s \in \sigma' \otimes \tau'$, which is compact.

Lastly, we need to show that $D_{\sigma \otimes \tau}$ satisfies diverge-or-reply. Indeed, suppose that $s \in \sigma \otimes \tau$ is an O -position and that $s \notin D_{\sigma \otimes \tau}$. Then $s|_{A,C} \notin D_\sigma$ and

$s|_{B,D} \notin D_\tau$. Using Lemma 3.6, we see that s must have one of the following sign profiles:

$$\begin{array}{cccc} \zeta_A(s|_A) & \zeta_B(s|_B) & \zeta_C(s|_C) & \zeta_D(s|_D) \\ \hline P & P & P & O \\ P & P & O & P \end{array}$$

It follows that one of $s|_{A,C}$ and $s|_{B,D}$ must be an O -position. Suppose without loss of generality that $s|_{A,C}$ is an O -position. Since $s|_{A,C} \notin D_\sigma$, there must be some move x such that $sx \in \sigma$, since σ satisfies diverge-or-reply. Then we have $sx \in \sigma \otimes \tau$. \square

We also need to show that the tensor product respects composition. This is easy.

Proposition 3.24. *Let A'', A', A, B'', B', B be games and let $\sigma': A'' \rightarrow A'$, $\sigma: A' \rightarrow A$, $\tau': B'' \rightarrow B'$, $\tau: B' \rightarrow B$ be strategies. Then*

$$(\sigma \otimes \tau) \circ (\sigma' \otimes \tau') = (\sigma \circ \sigma') \otimes (\tau \circ \tau')$$

Proof. At the level of trace sets, we have:

$$(\sigma \circ \sigma') \otimes (\tau \circ \tau') = \{s \in P_{(A'' \otimes B'') \rightarrow (A \otimes B)} : s|_{A'', A} \in \sigma \circ \sigma', s|_{B'', B} \in \tau \circ \tau'\}$$

Meanwhile:

$$\begin{aligned} (\sigma' \otimes \tau') \parallel (\sigma \otimes \tau) &= \left\{ \mathfrak{s} \in \overline{(M_{A'' \otimes B''} \sqcup M_{A' \otimes B'} \sqcup M_{A \otimes B})^*} \mid \begin{array}{l} \mathfrak{s}|_{A'' \otimes B'', A' \otimes B'} \in \sigma' \otimes \tau' \\ \mathfrak{s}|_{A' \otimes B', A \otimes B} \in \sigma \otimes \tau \end{array} \right\} \\ &= \left\{ \mathfrak{s} \in \overline{(M_{A'' \otimes B''} \sqcup M_{A' \otimes B'} \sqcup M_{A \otimes B})^*} \mid \begin{array}{l} \mathfrak{s}|_{A'', A'} \in \sigma' \\ \mathfrak{s}|_{A', A} \in \sigma \\ \mathfrak{s}|_{B'', B'} \in \tau' \\ \mathfrak{s}|_{B', B} \in \tau \end{array} \right\} \\ &= \left\{ \mathfrak{s} \in \overline{(M_{A'' \otimes B''} \sqcup M_{A' \otimes B'} \sqcup M_{A \otimes B})^*} \mid \begin{array}{l} \mathfrak{s}|_{A'', A', A} \in \sigma' \parallel \sigma \\ \mathfrak{s}|_{B'', B', B} \in \tau' \parallel \tau \end{array} \right\} \end{aligned}$$

It follows that

$$(\sigma \otimes \tau) \circ (\sigma' \otimes \tau') = \{\mathfrak{s}|_{A'' \otimes B'', A \otimes B} : \mathfrak{s} \in (\sigma' \otimes \tau') \parallel (\sigma \otimes \tau)\} = (\sigma \circ \sigma') \otimes (\tau \circ \tau')$$

We can show that

$$D_{(\sigma \otimes \tau) \circ (\sigma' \otimes \tau')} = D_{(\sigma \circ \sigma') \otimes (\tau \circ \tau')}$$

using a similar argument. \square

4 Denotational Semantics for Fair PCF

4.1 Soundness

4.2 Adequacy

I don't think I'll have a full abstraction result yet, but I could add a section explaining how this model gives us some progress towards full abstraction.

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