Fully Abstract Game Semantics for Actors

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Abstract. Along the way paved by the recent concurrent game semantics for process algebra CCS and π-calculus, based on the basic characteristics of the actor computational model and the very reductive semantics for actors, we establish a fully abstract concurrent game semantics for actors by borrowing the algebraic structure from CCS. This semantics can both be seen as an innocent presheaf semantics, and a concurrent game semantics.

Keywords: Game Semantics; Actors; Full Abstraction; Category; Presheaves

1. Introduction

As a concurrent computational model, actors [1][2] are well-known for capturing the so-called true concurrency. There are several semantic foundations for actors, like λ-calculus based reductive semantics for actors [3], rewriting semantics for actors [4][5][6].

On the other side, game semantics has gained great successes in modeling computations by use of games. To give actors a game semantics leads us to do some initial works [28][29] on this direction. But our previous works have at least two shortcomings: (1) The characteristics of actors supported are too little, e.g., there is not support for create action of actors; (2) A full abstractness result are not obtained.

In this paper, we establish a fully abstract game semantics for actors along the way paved by the recent works [25][26][27] on concurrent game semantics. This paper is organized as follows: in section 2, we introduce some preliminaries about actors and game semantics; we model actors as games in section 3, including the concepts of position, move, play and strategy, also the construction of the playground for actors; the full abstraction results are obtained in section 4; finally, we conclude and point out the future works in section5.
2. Preliminaries

For the conveniences of the reader, we introduce some preliminaries on actor computational model and game semantics.

2.1. Actors

An actor [1][2] is a concurrently computational model that encapsulates a set of states, a control thread and a set of local computations. It has a unique mail address and maintains a mailbox to accept messages sent by other actors. Actors do local computations by means of processing the messages stored in the mailbox sequentially and block when their mailboxes are empty.

During processing a message in mailbox, an actor may perform three candidate actions: (1) (send action) sending messages asynchronously to other actors by their mailbox addresses; (2) (create action) creating new actors with new behaviors; (3) (ready action) becoming ready to process the next message from the mailbox or block if the mailbox is empty. The illustration of an actor model are shown in Fig.1.

We abstract the basic characteristics from the above definition for actors.

1. The communication occurs through the mailbox of an actor, when two actor exchange their mailbox address, i.e., becoming acquaintances for each other, a communication channel is shared between them;
2. The mailbox address of actor can be sent out via send action by itself or by its acquaintances, to other unknown actors. This mechanism is some what like the channel mobility in π calculus;
3. An actor can create a new actor via create action, i.e., one actor forks into two avatars. Along with the creation of the new actor, a new mailbox (address) is also created. And also, the new actor inherits the original actor’s acquaintances, i.e., the mailbox addresses of the acquaintances of the original actor are also possessed by the new actor.
4. The actor address is unique to an actor and is always possessed by an actor, there is not any mailbox address drifting away from an actor.
5. We assume that the send action and the implicit receive action of the mailbox synchronize one time.

Since the lack of an algebraic foundation for actors [3], following the above ideas, we borrow some concepts from process algebra, and the actor processes will be infinite terms generated by the following typing rule:
Fig. 2. Game Semantics for the Function $f(x) = 3x + 10$ where $x \in \mathbb{N}$.

\[
\begin{array}{c|c|c}
\hline
\text{N} & \text{O} & \hline
\text{q} & \text{P} & \hline
\text{5} & \text{O} & \hline
\text{25} & \text{P} & \hline
\end{array}
\]

Where $\Gamma$ ranges over finite ordinals, viewed as a set of variables $\{1, \ldots, \Gamma\}$, $\alpha := \bar{a}(b)|a|\triangledown$ with $a, b \in \Gamma$, and $\triangledown$ is a tick action used to define successful execution.

2.2. Game Semantics

Game semantics gained the most great successes in introducing games into computer science. Game semantics models computations as playing of some kind of games, especially two player games. In the two player game, the Player (P) represents the system under consideration and the Opponent (O) represents the environment in which the system is located. In game semantics, the behaviors of the system (acts as P) and the environment (acts as O) are explicitly distinguished. So the interactions between the system and the environment can be captured by game plays between the opponent and the player, and successful interactions can be captured by the game strategy.

For example, the function $f(x) = 3x + 10$ where $x \in \mathbb{N}$ can be deemed as the games played in Fig.2. Firstly, the opponent (the environment) moves to ask the value of $f(x)$, then the player (the function) moves to ask the value of $x$, and then the opponent moves to answer that the value of $x$ is 5, the player moves to answer that the value of $f(x)$ is 25 finally.

Game semantics has gained great successes in modeling computations, such as an initial success of modeling the functional programming language PCF (Programming Computable Functions)[7][8], multiplicative linear logic [9], general reference[10], etc. To model concurrency in computer science with game semantics, a new kind of game semantics called asynchronous game [13][14][15][16][17] is established and a bridge between the asynchronous game and traditional game semantics is founded. Moreover, asynchronous games perfectly model propositional linear logic and get a full completeness result. Another kind of game semantics to describe concurrency is concurrent game[11][12], and a work to bridge asynchronous game and concurrent game is introduced in [17].

Recently, a new kind of concurrent game semantics based on category theory is introduced in citations [25][26][27]. This kind of semantics can both be seen as an innocent presheaf semantics, and a concurrent game semantics. Full abstraction result for fair testing equivalence [23][24] in CCS [26] and $\pi$ [27] are obtained. Our works for actors are along the way paved by this new kind of semantics.

3. Modeling Actors as Games

Since actors are modeled as games, we introduce the main works in this section, including the concept of position, move, play and strategies, also the construction of the playground for actors.

In this paper, any finite ordinal $n$ is seen as $\{1, \ldots, n\}$. Set is the category of sets, set is the category of finite ordinals and arbitrary maps, ford is the category of finite ordinals and monotone maps. For any category $\mathbb{C}$, $\hat{\mathbb{C}} = [\mathbb{C}^{\text{op}}, \text{Set}]$, $\overline{\mathbb{C}} = [\mathbb{C}^{\text{op}}, \text{set}]$, $\check{\mathbb{C}} = [\mathbb{C}^{\text{op}}, \text{ford}]$, $\hat{\mathbb{C}}^f$ denotes the category of finite presheaves.
3.1. Positions

Positions are graph-like objects, where players and communication channels are represented by vertices. By citations [25][26], the directed multi graphs (string diagrams) are represented as presheaves \( G \) over the category \( \mathbb{C} \) freely generated by the graph.

Firstly, let us give the definition of the base category \( \mathbb{C} \).

**Definition 1 (The Base Category \( \mathbb{C} \)).** Let \( G_\mathbb{C} \) be the graph with \( n, m \in \mathbb{N} \) and \( a, b \in n \) and \( c, d \in m \), and

- vertices \( *, [n], \pi_n^l, \pi_n^r, \pi_n, \triangledown_n, \iota_{n,a}, o_{n,a,b}, \tau_{n,a,m,c,d} \);
- edges \( s_1, ..., s_n : * \to [n] \);
- for all \( v \in \{\triangledown_n, o_{n,a,b}\} \), edges \( s, t : [n] \to v \);
- edges \( [n] \xrightarrow{t} \pi_n^l \xleftarrow{r} [n + 1] \), \( [n] \xrightarrow{t} \pi_n^r \xleftarrow{r} [n + 1] \);
- edges \( \pi_n^l \xrightarrow{t} \pi_n \xleftarrow{r} \pi_n^r \);
- edges \( \iota_{n,a} \xrightarrow{t} \tau_{n,a,m,c,d} \xleftarrow{r} o_{m,c,d} \).

Let the base category \( \mathbb{C} \) be the freely generated category on \( G_\mathbb{C} \), modulo the equations in Fig.3.

To visualize how such presheaves \( G \) represent such graphs, there is a way by computing their categories of elements. Citations [25] and [26] state that the category of elements for a presheaf \( G \) over \( \mathbb{C} \) has as objects pairs \((c, x)\), where \( c \in \mathbb{C} \) and \( x \in G(c) \), and as morphisms \((c, x) \to (d, y)\) with all morphisms \( f : c \to d \) in \( \mathbb{C} \) such that \( y \cdot f = x \).

The positions are finite presheaves \( G \) empty except perhaps on \( * \) and \([n]\)'s. And other objects in \( G \) will represent moves. The above definition seems a little arbitrary, but we give some explanations for the above definition of the base category \( \mathbb{C} \).

Moves are derived from the very definition of actors, i.e., the reduction semantics of actors[3]. We give some intuitions.

1. \( \pi_n \) is the forking move, which corresponds to the create action of actors, i.e., an actor can create a new actor during its execution. Both the original actor and the newly created actor share the knowledge of their acquaintances, i.e., knowledge of mailboxes of their acquaintances or communication channels. More importantly, when a new actor is created, a new mailbox of the newly created actor is also created and it exchanges its new mailbox with the original actor, such that a new communication channel is shared by the two avatars. In \( \pi_n \), \( n \) represents the shared \( n \) communication channels.

2. \( \triangledown_n \) is a tick move, which is to define successful plays. It is useful to define testing equivalence.

3. \( \tau_{n,a,m,c,d} \) is to model synchronization between two players involved in the synchronization. Here, \( n \) and \( m \) represent the numbers of channels known to the players, and \( a, c \) represent the indexes of the channels where the synchronization occurs since the channels known to a player are ordered. And \( d \) represents the channel index of the output player which is carried during the synchronization, since actors may exchange their acquaintances with each other.

4. Since the final position of \( \pi_n \) and \( \tau_{n,a,m,c,d} \) has more than one player, to get a more fine-grained structure for moves, they must be decomposed into basic moves. \( \pi_n \) is decomposed into left half-forking \( \pi_n^l \) and right half-forking \( \pi_n^r \), also \( \tau_{n,a,m,c,d} \) is decomposed into input move \( \iota_{n,a} \) and output move \( o_{m,c,d} \).

In citations [25] and [26], left half-forking move \( \pi_n^l \), right half-forking \( \pi_n^r \), input move \( \iota_{n,a} \), output move \( o_{m,c,d} \), and tick move \( \triangledown_n \) are called basic moves; and forking move \( \pi_n \), synchronization move \( \tau_{n,a,m,c,d} \), and tick move \( \triangledown_n \) are called closed world move, which represent that a group of players evolve on their own in isolation.

3.2. Moves

Moves are not just a binary relation between positions, they contains information explaining not only when there is a move from one position to another, but also how a move from one position to another.

**Definition 2 (Move).** For each diagram \( M \) representing a move, its initial and final positions, \( X \) and
Y, are defined and the whole move is defined as a cospan $Y \xrightarrow{t} M \xleftarrow{t} X$. Where the time flows from the right to the left.

From Definition 1, we get the following definition.

**Definition 3 (Seed).** The following cospans are called seeds. Their lower legs are called t-legs. And seeds from 3 to 7 are called basic seeds. Note that the time also flows from the right to the left.

1. $[n+1][n+1] \to \pi_n \leftarrow [n]$:
2. \([m]_{c,d} \rightarrow \tau_{n,a,m,c,d} \leftarrow [m]_{c,a}[n]n + 1\); 
3. \([n + 1] \rightarrow \pi_n' \leftarrow [n];\)
4. \([n + 1] \rightarrow \pi_n^a \leftarrow [n];\)
5. \([m] \rightarrow \alpha_{m,c,d} \leftarrow [m];\)
6. \([n + 1] \rightarrow \tau_{n,a} \leftarrow [n];\)
7. \([n] \rightarrow \nu_n \leftarrow [n].\)

The extended moves are obtained by embedding seeds into bigger positions, i.e., in which seeds are allowed to occur with more than one player.

**Definition 4 (Interface of A Seed)**. Let the interface of a seed \(Y \rightarrow M \leftarrow X\) be \(I_X = X(\ast) \cdot \ast\), i.e., a presheaf \(I\) and morphisms \(X \leftarrow I \rightarrow Y\) and following diagram

\[
\begin{array}{ccc}
I & \rightarrow & Y \\
\downarrow & & \downarrow \\
X & \rightarrow & M
\end{array}
\]

commutes. The position \(I_X\) consists only of the channels of the initial position of the seed.

**Definition 5 (Extended Move)**. An extended move is obtained by gluing any position \(Z\) to the seed with its interface, equipped with a morphisms \(I_X \rightarrow Z\), a new cospan \(Y' \rightarrow M' \leftarrow X'\) is obtained by the universal property of pushout.

3.3. Plays

We use the composition of (extended) moves to define plays.

**Definition 6 (Play)**. A play is composite of (extended) moves in \(\text{Cospan}(\mathcal{C})\). Let \(\mathbb{D}_e\) be the subbicategory of \(\text{Cospan}(\mathcal{C})\), which has as objects all finite presheaves on \(\mathcal{C}\), as morphisms \(X \rightarrow Y\) all conspans \(Y \rightarrow U \leftarrow X\), and as 2-cells \(U \rightarrow V\), such that the following diagram commutes.
3.4. Playground for Actors

To construct the playground for actors, we need three steps:

1. adding a new dimension to $D_v$ to form a pseudo double category $\mathbb{D}$;
2. showing that the vertical codomain functor is a (Grothendieck) fibration $\mathbb{D}_h$;
3. showing that $\mathbb{D}$ forms a playground.

Firstly, we introduce some preliminaries about the pseudo double category. A pseudo double category $\mathbb{D}$ consists of a set $\text{ob}(\mathbb{D})$ of objects, which are shared by a horizontal category $\mathbb{D}_h$ and a vertical bicategory $\mathbb{D}_v$, where $\mathbb{D}_h$ is a mere category and has standard normal arrows $\rightarrow$ and composition $\circ$, while $\mathbb{D}_v$ has arrows $\rightrightarrows$ and composition $\bullet$. $\mathbb{D}$ also has a set of double cells $\alpha$, which has vertical domain and codomain, horizontal domain and codomain, denoted as $\text{dom}_v(\alpha)$, $\text{cod}_v(\alpha)$, $\text{dom}_h(\alpha)$ and $\text{cod}_h(\alpha)$.

We let $\mathbb{H} \subseteq \hat{\mathbb{C}}$ be the identity-on-objects subcategory of natural transformations with injective components, except perhaps on channels. And for $\mathbb{D}_h$, we take the full subcategory of $\mathbb{H}$ spanning positions. Thus, we make $\mathbb{D}$ form a pseudo double category, and the following diagram in Fig.4 commutes.

Let $\mathbb{D}_H$ denote the category with vertical morphisms as objects and double cells as morphisms. Now, we show that the vertical codomain functor $\text{cod}_v : \mathbb{D}_H \rightarrow \mathbb{D}_h$ is a (Grothendieck) fibration.

It follows that fact from [21][22] that a strong factorization system on a category $\mathbb{C}$ consists of two subcategory $\mathbb{L}$ and $\mathbb{R}$ of $\mathbb{C}$, both containing all isomorphisms, such that any morphism in $\mathbb{C}$ factors essentially uniquely as $r \circ l$ with $l \in \mathbb{L}$ and $r \in \mathbb{R}$.

Here, for any morphism $f : A \rightarrow B$ and $g : C \rightarrow D$, $f \perp g$ denotes that for all commuting squares as the following diagram shows, there is a unique lifting $h$ making both triangles commute.

$$
\begin{array}{ccc}
A & \xrightarrow{u} & C \\
\downarrow^{f} & & \downarrow^{h} \\
B & \xrightarrow{v} & D
\end{array}
$$

$L \perp R$ extends to classes of morphisms, and $L^\perp = \{g| L \perp \{g\}\}$, $R^\perp = \{f| \{f\} \perp R\}$.

We give the Bousfield’s construction[19][22] of factorization systems, which is the basis of our factorization system. It says that, for any class $T$ of morphisms in any locally presentable category $\mathbb{E}$, the pair $(\perp(T^\perp), T^\perp)$ forms a factorization system.

Similarly to citation[27], we construct the double category $\mathbb{D}_{L,R}$, where $L = \perp(T^\perp)$ and $R = T^\perp$, and

- vertical morphisms $X \rightarrow Y$ are cospans $X \xleftarrow{f} U \xrightarrow{l} Y$ with $l \in L$;
- horizontal morphisms are morphisms in $R$;
- double cells are diagrams like Fig.4 with all double cells in $R$.

This leads to the following Proposition 1.

**Proposition 1.** The functor $\text{cod}_v : (\mathbb{D}_{L,R})_H \rightarrow (\mathbb{D}_{L,R})_h$ is a fibration.

By applying Bousfield’s construction of factorization systems to the set of all $t$-legs of seeds defined in Definition 3, we can get a factorization system $(L, R)$ on $\hat{\mathbb{C}}$. And this factorization keeps in $\hat{\mathbb{C}}$, $\mathbb{H}$ is
contained in \( R \) and stable under pullback, and has the left cancellation property. This yields to the following Proposition 2.

**Proposition 1.** The functor \( \text{cod}_v : \mathcal{D}_H \to \mathcal{D}_h \) is a fibration.

By checking other axioms about a playground, we get the following result.

**Theorem 1.** \( \mathcal{D} \) forms a playground.

### 3.5. Strategies

Following citations [25][26][27], we now discuss the category of strategies \( S_X \) associating with a position \( X \).

In a playground, the analogue of the poset of plays with prefix order is given by the category \( \mathcal{P}(X) \) with plays \( u : Y \to X \) as objects and double cells \( u \to u' \) as morphisms, as the following diagram shows. Let the category \( \mathcal{B}_X \) of behaviors on \( X \) be \( \mathcal{P}(X) \).

![Diagram of plays and double cells]

To make local behavior be irrelevant when gluing to the globally more bigger behavior, innocence is introduced into strategies. Since basic seeds defined in Definition 3 are with one player, and views are composites of these basic seeds in \( \mathcal{D}_v \). We replace \( \mathcal{P}(X) \) by \( \mathcal{V}_X \) with pairs \( (v,x) \) as objects and double cells \( v \to v' \) as morphisms, as the following diagram shows.

![Diagram of views and double cells]

Now, we can get the following definition.

**Definition 7 (Strategies).** Let the category of strategies \( S_X \) over \( X \) be \( \mathcal{V}_X \).

We also introduce the category \( \mathcal{F}_X \) to relate strategies and behaviors, which has pairs \( (u,h) \) as objects, and \( (u,h) \to (u',h') \) as morphisms, as the following diagram shows. This makes spatial information included.
Also, Right Kan extension and restriction along $\forall_X^\text{op} \hookrightarrow \mathbb{P}_X^\text{op} \leftarrow \mathbb{P}(X)^\text{op}$ induce a functor $\mathbf{S}_X \to \mathbf{B}_X$.

4. Full Abstraction for Fair Testing in Actors

Construction of the playground [26][27] state that strategies over the playground $D$ are entirely described by the following typing rules

$$
\begin{align*}
\vdash n \cdot n_B \vdash S_B \cdots (\forall B : [n_B] \to [n]), \\
n \vdash D_i \vdash (n_B)_{B \in \mathbb{B}_n} \\
\vdash n \vdash D_i \cdots (\forall i \in m, m \in \mathbb{N}) \\
\vdash n \vdash \oplus_{i \in m} D_i,
\end{align*}
$$

where $\mathbb{B}_n$ is the set of basic seeds from $[n]$ as defined in Definition 3.

The following conclusion from [26], says that "Strategies over $[n]$ are in bijection with possibly infinite terms in context $n$. Furthermore, giving a strategy over any position $X$ amounts to giving a strategy over $[n]$ for each $n$-ary player of $X$.” We get the following interpretation of processes.

$$
[\Gamma \vdash \bigoplus_i \alpha_i, P_i] = (B \mapsto \oplus_{i \in \mathbb{B}_n} [\Gamma \cdot \alpha_i \vdash P_i]),
$$

$$
[\Gamma \vdash P \mid Q] = ([\Gamma \vdash P] \mapsto [\Gamma \vdash P + Q] \quad [\Gamma \vdash Q] \mapsto [\Gamma \vdash Q] - \mapsto \emptyset),
$$

where $[\bar{a}(b)] = o_{\tau, a, b}$, $[a] = \tau_{\Gamma, a}$, $[\bigcup] = \nabla_{\tau}$, $\emptyset$ is the empty $\oplus$, and $- \mapsto \emptyset$ is applied to undefined basic seeds not in Definition 3.

Let the derivation operation be $\partial_B((S_B)_{B \in \mathbb{B}_n}) = S_B$, and the partial restriction operation be $(\oplus_{P \in P(D)}|_{\Gamma} = D_i, i \in \mathbb{P})$. Let $\mathbf{S}_D$ denotes free reflexive graph with as vertices pairs of a position $X$ and a definite strategy $D$ over $X$, and as edges all well-defined triples $(X, D) \xrightarrow{M} (Y, (D_M D)|_i)$, for all moves $M : Y \to X$.

For any state $(X, D)$ of $\mathbf{S}_D$, a test for $(X, D)$ is a pair of a horizontal morphism $h : I_X \to Y$ and a strategy $T$ on $Y$. Whether such a test is successful will be determined by the closed-world dynamics of the strategy $(D, T)$ over the pushout $Z = X + I_X Y$. Similarly, let $\mathbf{S}_D^\text{BW}$ be the close-world part of $\mathbf{S}_D$, consisting of edges whose underlying moves are close-world moves including forking move $\pi_n$, synchronization move $\tau_{n, a, m, c, d}$, or tick move $\nabla_n$.

There is a morphism of reflexive graphs to the one-vertex reflexive graph with one non-identity edge $\nabla$, denoted by $(X, D) \xrightarrow{\nabla} (X', D')$. Let $\bot^D$ denote the set of all vertices $x$ of $\mathbf{S}_D$, for all $x \to x'$, there exists $x^\prime$ such that $x \xrightarrow{\nabla} x''$. Let $(X, D)^\perp$ be the set of all tests $(h, T)$ such that $(D, T) \in \bot^D$, let $(X, D) \sim (X', D')$ iff $(X, D)^\perp = (X', D')^\perp$. Let $\bot^D$ denote the set of all vertices $x$ of $P_i$, for all $x \to x'$, there exists $x'$ such that $x \xrightarrow{\nabla} x''$. Let $(\Gamma \vdash P)^\perp$ be the set of all tests $(h, R)$ such that $(P(h)|R) \in \bot^D$, let $(\Gamma \vdash P) \sim (\Gamma \vdash Q)$ iff $(\Gamma \vdash P)^\perp = (\Gamma \vdash Q)^\perp$.

**Theorem 2.** For all $P, Q$, $(\Gamma \vdash P) \sim (\Gamma \vdash Q)$ iff $([\Gamma], [P]) \sim^B ([\Gamma], [Q])$. 
Proof. Firstly, we make $S_D$ be obvious to infer the transitions of a vertex $(X, D)$ from the transitions of the player $X$. Let us design a finer LTS $S_{LD}$ for $D$, whose vertices are triples $(I, h, S)$ with an interface $I$ representing all channels known to the environment, a horizontal map $h : I \rightarrow X$ and a strategy $S$ over $X$. $S_{LD}$ makes all transitions can be completed into closed-world transitions by interacting at $I$.

Then, we coarsen $S_{LD}$ to a new LTS $S_AD$, where the new free reflexive graph $A$ has vertices of maps $\Delta \rightarrow \Gamma$, and edges defined in Fig.5, where $\Delta$ denotes the channels of the interface and $\Gamma$ represents the channels that the considered actor or strategy known locally.

In Fig.5, the rules from the first to the fifth are the same as in citation [27], they are for tick, input, output and synchronization. The last three rules are for left forking, right forking and forking. Left forking and right forking create fresh channels which are private to the actor, and forking create a new channel for both $\Delta$ and $\Gamma$.

So, we can view $S_D$ as an LTS $S_{A\Delta}$ over $A\Delta$, and $P_i^h$ can also be viewed as an LTS over $A\Delta$. Then we can define when these transitions in $A\Delta$ are complementary, and fair testing equivalence in $P_\pi$ and $S_D$ can be checked in terms of transitions over $A\Delta$, i.e., for a process $P$ and a testing $T$ and $P|T \rightarrow Q$, $P \xrightarrow{w'} P'$ and $T \xrightarrow{w'} T'$, $Q = P'|T'$ can be replaced.

Finally, we can prove that the translation $[-] : P_i \rightarrow S_D$ is surjective up to weak bisimilarity (except for empty strategies).

Then the below conclusion follows.

**Theorem 3.** For all strategies $S$ over $[\Gamma]$, there exists a process $\Gamma \vdash P$ such that $[\Gamma \vdash P] \sim^D ([\Gamma], S)$. 

5. Conclusions

Along the way paved by citation [25][26][27], a fully abstract concurrent game semantics for actors is established. This work is based on the basic characteristics of actor computational model [1][2] and the very reductive semantics of actors [3], by borrowing algebraic structure of process algebra. There are two limitations that we will conquer in future: (1) The inner computations of an actor are not explicitly considered in this paper; (2) The reductive semantics in citation [3] has more richer semantics than our works, which is based $\lambda$-calculus. Considering the full semantics for actors in a game semantics flavor is really a challenge.
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