Decorated proofs for computational effects: States
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Abstract

The syntax of an imperative language does not mention explicitly the state, while its
denotational semantics has to mention it. In this paper we show that the equational proofs about an
imperative language may hide the state, in the same way as the syntax does.

Introduction

The evolution of the state of the memory in an imperative program is a computational effect: the state
is never mentioned as an argument or a result of a command, whereas in general it is used and modified
during the execution of commands. Thus, the syntax of an imperative language does not mention explicitly
the state, while its denotational semantics has to mention it. This means that the state is 
encapsulated:
its interface, which is made of the functions for looking up and updating the values of the locations, is
separated from its implementation; the state cannot be accessed in any other way than through his interface.
In this paper we show that equational proofs in an imperative language may also encapsulate the state:
proofs can be performed without any knowledge of the implementation of the state. We will see that a naive
approach (called “apparent”) cannot deal with the updating of states, while this becomes possible with
a slightly more sophisticated approach (called “decorated”). This is expressed in an algebraic framework
relying on category theory. To our knowledge, the first categorical treatment of computational effects, using
monads, is due to Moggi [Moggi 1991]. The examples proposed by Moggi include the side-effects monad
\( T(A) = (A \times St)St \) where \( St \) is the set of states. Later on, Plotkin and Power used Lawvere theories for
dealing with the operations and equations related to computational effects. The Lawvere theory for the
side-effects monad involves seven equations [Plotkin & Power 2002]. In Section 1 we describe the intended
denotational semantics of states. Then in Section 2 we introduce three variants of the equational logic for
formalizing the computational effects due to the states: the apparent, decorated an explicit logics. This
approach is illustrated in Section 3 by proving some of the equations from [Plotkin & Power 2002], using
rules which do not mention any type of states.

1 Motivations

This section is made of three independent parts. Section 1.1 is devoted to the semantics of states, an example
is presented in Section 1.2 and our logical framework is described in Section 1.3
1.1 Semantics of states

This section deals with the denotational semantics of states, by providing a set-valued interpretation of the `lookup` and `update` operations. Let $\mathcal{S}$ denote the set of states. Let $\text{Loc}$ denote the set of locations (also called variables or identifiers). For each location $i$, let $\text{Val}_i$ denote the set of possible values for $i$. For each location $i$ there is a `lookup` function for reading the value of location $i$ in the given state, without modifying this state: this corresponds to a function $\text{lookup}_{i,1} : \mathcal{S} \to \text{Val}_i$ or equivalently to a function $\text{lookup}_i : \mathcal{S} \to \text{Val}_i \times \mathcal{S}$ such that $\text{lookup}_i(s) = (\text{lookup}_{i,1}(s), s)$ for each state $s$. In addition, for each location $i$ there is an `update` function $\text{update}_i : \text{Val}_i \times \mathcal{S} \to \mathcal{S}$ for setting the value of location $i$ to the given value, without modifying the values of the other locations in the given state. This is summarized as follows, for each $i \in \text{Loc}$: a set $\text{Val}_i$, two functions $\text{lookup}_{i,1} : \mathcal{S} \to \text{Val}_i$ and $\text{update}_i : \text{Val}_i \times \mathcal{S} \to \mathcal{S}$, and equations (1):

\[
\begin{align*}
(1.1) & \forall a \in \text{Val}_i, \forall s \in \mathcal{S}, \text{lookup}_{i,1}(\text{update}_i(a, s)) = a, \\
(1.2) & \forall a \in \text{Val}_i, \forall s \in \mathcal{S}, \text{lookup}_{j,1}(\text{update}_i(a, s)) = \text{lookup}_{j,1}(s) \quad \text{for every } j \in \text{Loc}, j \neq i.
\end{align*}
\]

The state can be observed thanks to the lookup functions. We may consider the tuple $\langle \text{lookup}_{i,1} \rangle_{i \in \text{Loc}} : \mathcal{S} \to \prod_{i \in \text{Loc}} \text{Val}_i$. If this function is an isomorphism, then Equations (1) provide a definition of the update functions. In [Plotkin & Power 2002] an equational presentation of states is given, with seven equations: in Remark 1.1 these equations are expressed according to [Mellies 2010] and they are translated in our framework. We use the notations $l_i = \text{lookup}_{i,1} : \mathcal{S} \to \text{Val}_i \times \mathcal{S}$, $l_{i,1} = \text{lookup}_{i,1} : \mathcal{S} \to \text{Val}_i$, and $u_i = \text{update}_i : \text{Val}_i \times \mathcal{S} \to \mathcal{S}$, and in addition $i_d_i : \mathcal{S} \to \text{Val}_i$, and $q_i : \text{Val}_i \times \mathcal{S} \to \mathcal{S}$ respectively denote the identity of $\text{Val}_i$ and the projection, while $\text{perm}_{i,j} : \text{Val}_i \times \mathcal{S} \to \text{Val}_j \times \mathcal{S}$ permutes its first and second arguments.

**Remark 1.1.** The equations in [Plotkin & Power 2002] can be expressed as the following Equations (2):

\[
\begin{align*}
(2.1) & \text{Annihilation lookup-update.} \quad \text{Reading the value of a location } i \text{ and then updating the location } i \text{ with the obtained value is just like doing nothing.} \\
& \quad \forall i \in \text{Loc}, \forall s \in \mathcal{S}, \quad u_i(l_i(s)) = s \in \mathcal{S} \\
(2.2) & \text{Interaction lookup-lookup.} \quad \text{Reading twice the same location loc is the same as reading it once.} \\
& \quad \forall i \in \text{Loc}, \forall s \in \mathcal{S}, \quad l_i(q_i(l_i(s))) = l_i(s) \in \text{Val}_i \times \mathcal{S} \\
(2.3) & \text{Interaction update-update.} \quad \text{Storing a value } a \text{ and then a value } a' \text{ at the same location } i \text{ is just like storing the value } a' \text{ in the location.} \\
& \quad \forall i \in \text{Loc}, \forall s \in \mathcal{S}, \forall a, a' \in \text{Val}_i, \quad u_i(a', u_i(a, s)) = u_i(a', s) \in \mathcal{S} \\
(2.4) & \text{Interaction update-lookup.} \quad \text{When one stores a value } a \text{ in a location } i \text{ and then reads the location } i, \text{ one gets the value } a. \\
& \quad \forall i \in \text{Loc}, \forall s \in \mathcal{S}, \forall a \in \text{Val}_i, \quad l_{i,1}(u_i(a, s)) = a \in \text{Val}_i \\
(2.5) & \text{Commutation lookup-update.} \quad \text{The order of reading two different locations } i \text{ and } j \text{ does not matter.} \\
& \quad \forall i \neq j \in \text{Loc}, \forall s \in \mathcal{S}, \quad (i_d_i \times l_j)(l_i(s)) = \text{perm}_{i,j}((i_d_j \times l_i)(l_j(s))) \in \text{Val}_i \times \text{Val}_j \times \mathcal{S} \\
(2.6) & \text{Commutation update-update.} \quad \text{The order of storing in two different locations } i \text{ and } j \text{ does not matter.} \\
& \quad \forall i \neq j \in \text{Loc}, \forall s \in \mathcal{S}, \forall a \in \text{Val}_i, \forall b \in \text{Val}_j, \quad u_j(b, u_i(a, s)) = u_i(a, u_j(b, s)) \in \mathcal{S} \\
(2.7) & \text{Commutation update-lookup.} \quad \text{The order of storing in a location } i \text{ and reading in another location } j \text{ does not matter.} \\
& \quad \forall i \neq j \in \text{Loc}, \forall s \in \mathcal{S}, \forall a \in \text{Val}_i, \quad l_j(u_i(a, s)) = (i_d_j \times u_i)(\text{perm}_{i,j}(a, l_j(s))) \in \text{Val}_j \times \mathcal{S}
\end{align*}
\]

**Proposition 1.2.** Let us assume that $\langle l_{i,1} \rangle_{i \in \text{Loc}} : \mathcal{S} \to \prod_{i \in \text{Loc}} \text{Val}_i$ is invertible. Then Equations (1) are equivalent to Equations (2).
Proof. It may be observed that (2.4) is exactly (1.1). In addition, (2.7) is equivalent to (1.2): indeed, (2.7) is equivalent to the conjunction of its projection on \( Val \) and its projection on \( St \); the first one is \( l_{ij}(a, s) = l_{ij}(s) \), which is (1.2), and the second one is \( u_i(a, s) = u_i(a, s) \). Equations (2.2) and (2.5) follow from \( q_i(l_{i}(s)) = s \). For the remaining equations (2.1), (2.3) and (2.6), which return states, it is easy to check that for each location \( k \), by applying \( l_k \) to both members and using equation (1.1) or (1.2) according to \( k \), we get the same value in \( Val_k \) for both hand-sides. Then equations (2.1), (2.3) and (2.6) follow from the fact that \( (l_{i,1})_{i \in Loc} : St \rightarrow \prod_{i \in Loc} Val_i \) is invertible.

Proposition 1.2 will be revisited in Section 3, where it will be proved that equations (1) imply equations (2) without ever mentioning explicitly the state in the proof.

1.2 Computational effects: an example

In an informal way, we consider that a computational effect occurs when there is an apparent mismatch, i.e., some lack of soundness, between the syntax and the denotational semantics of a language. For instance in an object-oriented language, the state of an object does not appear explicitly as an argument nor as a result of any of its methods. In this section, as a toy example, we build a class BankAccount for managing (very simple!) bank accounts. We use the types \( \text{int} \) and \( \text{void} \), and we assume that \( \text{int} \) is interpreted by the set of integers \( \mathbb{Z} \) and \( \text{void} \) by a singleton \( \{\star\} \). In the class BankAccount, there is a method \( \text{balance()} \) which returns the current balance of the account and a method \( \text{deposit(x)} \) for the deposit of \( x \) Euros on the account. The \( \text{deposit} \) method is a \textit{modifier}, which means that it can use and modify the state of the current account. The \( \text{balance} \) method is an \textit{inspector}, or an \textit{accessor}, which means that it can use the state of the current account but it is not allowed to modify this state. In the object-oriented language C++, a method is called a \textit{member function}; by default a member function is a modifier, when it is an accessor it is called a \textit{constant member function} and the keyword \texttt{const} is used. So, the C++ syntax for declaring the member functions of the class BankAccount looks like:

```
int balance ( ) const ;
void deposit ( int ) ;
```

- Forgetting the keyword \texttt{const}, this piece of C++ syntax can be translated as a signature \( \text{Bank}_{\text{app}} \), which we call the \textit{apparent signature} (we use the word “apparent” in the sense of “seeming” i.e., “appearing as such but not necessarily so”).

\[
\begin{align*}
\text{Bank}_{\text{app}} : & \begin{cases}
\text{balance} : \text{void} \rightarrow \text{int} \\
\text{deposit} : \text{int} \rightarrow \text{void}
\end{cases}
\end{align*}
\]

In a model (or algebra) of the signature \( \text{Bank}_{\text{app}} \), the operations would be interpreted as functions:

\[
\begin{align*}
[[\text{balance}]] : \{\star\} \rightarrow \mathbb{Z} \\
[[\text{deposit}]] : \mathbb{Z} \rightarrow \{\star\}
\end{align*}
\]

which clearly is not the intended interpretation.

- In order to get the right semantics, we may use another signature \( \text{Bank}_{\text{expl}} \), which we call the \textit{explicit signature}, with a new symbol \texttt{state} for the “type of states”:

\[
\begin{align*}
\text{Bank}_{\text{expl}} : & \begin{cases}
\text{balance} : \text{state} \rightarrow \text{int} \\
\text{deposit} : \text{int} \times \text{state} \rightarrow \text{state}
\end{cases}
\end{align*}
\]

The intended interpretation is a model of the explicit signature \( \text{Bank}_{\text{expl}} \), with \( St \) denoting the set of states of a bank account:

\[
\begin{align*}
[[\text{balance}]] : St \rightarrow \mathbb{Z} \\
[[\text{deposit}]] : \mathbb{Z} \times St \rightarrow St
\end{align*}
\]
So far, in this example, we have considered two different signatures. On the one hand, the apparent signature Bank\text{app} is simple and quite close to the C++ code, but the intended semantics is not a model of Bank\text{app}. On the other hand, the semantics is a model of the explicit signature Bank\text{expl}, but Bank\text{expl} is far from the C++ syntax: actually, the very nature of the object-oriented language is lost by introducing a “type of states”. Let us now define a decorated signature Bank\text{deco}, which is still closer to the C++ code than the apparent signature and which has a model corresponding to the intended semantics. The decorated signature is not exactly a signature in the classical sense, because there is a classification of its operations. This classification is provided by superscripts called decorations: the decorations (1) and (2) correspond respectively to the object-oriented notions of accessor and modifier.

\[
\text{Bank}\text{deco} : \begin{align*}
\text{balance}^{(1)} : & \text{void} \to \text{int} \\
\text{deposit}^{(2)} : & \text{int} \to \text{void}
\end{align*}
\]

The decorated signature is similar to the C++ code, with the decoration (1) corresponding to the keyword const. The apparent specification Bank\text{app} may be recovered from Bank\text{deco} by dropping the decorations. In addition, we claim that the intended semantics can be seen as a decorated model of this decorated signature: this will become clear in Section 2.3. In order to add to the apparent and explicit signatures the constants int like 0, 1, 2, . . . and the usual operations on integers, a third decoration is used: the decoration (0) for pure functions, which means, for functions which neither inspect nor modify the state of the bank account. So, we add to the apparent and explicit signatures the constants 0, 1, . . . : void \to int and the operations +, -, \times : int \times int \to int, and we add to the decorated signature the pure constants 0\text{(0)}, 1\text{(0)}, . . . : void \to int and the pure operations +\text{(0)}, -\text{(0)}, \times\text{(0)} : int \times int \to int. For instance the C++ expressions

\[
deposit(7); \text{balance()} \quad \text{and} \quad 7 + \text{balance()}\
\]

can be seen as the decorated terms:

\[
\text{balance}^{(1)} \circ \text{deposit}^{(2)} \circ \text{7\text{(0)}} \quad \text{and} \quad +\text{(0)} \circ \langle \text{7\text{(0)}}, \text{balance}^{(1)} \rangle
\]

which may be illustrated as:

\[
\text{void} \xrightarrow{7\text{(0)}} \text{int} \xrightarrow{\text{deposit}^{(2)}} \text{void} \xrightarrow{\text{balance}^{(1)}} \text{int} \quad \text{and} \quad \text{void} \xrightarrow{\langle \text{7\text{(0)}}, \text{balance}^{(1)} \rangle} \text{int} \times \text{int} \xrightarrow{+\text{(0)}} \text{int}
\]

These two decorated terms have different effects: the first one does modify the state while the second one is an accessor; however, both return the same integer. Let us introduce the symbol \sim for the relation “same result, maybe distinct effects”. Then:

\[
\text{balance}^{(1)} \circ \text{deposit}^{(2)} \circ \text{7\text{(0)}} \quad \sim \quad +\text{(0)} \circ \langle \text{7\text{(0)}}, \text{balance}^{(1)} \rangle
\]

1.3 Diagrammatic logics

In this paper, in order to deal with a relevant notion of morphisms between logics, we define a logic as a diagrammatic logic, in the sense of [Domínguez & Duval 2010]. For the purpose of this paper let us simply say that a logic \( \mathcal{L} \) determines a category of theories \( \mathbf{T} \) which is cocomplete, and that a morphism of logics is a left adjoint functor, so that it preserves the colimits. The objects of \( \mathbf{T} \) are called the \emph{theories} of the logic \( \mathcal{L} \). Quite often, \( \mathbf{T} \) is a category of structured categories. The \emph{inference rules} of the logic \( \mathcal{L} \) describe the structure of its theories. When a theory \( \Phi \) is generated by some presentation or specification \( \Sigma \), a model of \( \Sigma \) with values in a theory \( \Theta \) is a morphism \( M : \Phi \to \Theta \) in \( \mathbf{T} \).
The monadic equational logic. For instance, and for future use in the paper, here is the way we describe the monadic equational logic \( \mathcal{L}_{\text{meq}} \). In order to focus on the syntactic aspect of the theories, we use a congruence symbol “\( \equiv \)” rather than the equality symbol “\( = \)”. Roughly speaking, a monadic equational theory is a sort of category where the axioms hold only up to congruence (in fact, it is a 2-category). Precisely, a monadic equational theory is a directed graph (its vertices are called objects or types and its edges are called morphisms or terms) with an identity term \( \text{id}_X : X \to X \) for each type \( X \) and a composed term \( g \circ f : X \to Z \) for each pair of consecutive terms \( (f : X \to Y, g : Y \to Z) \); in addition it is endowed with equations \( f \equiv g : X \to Y \) which form a congruence, which means, an equivalence relation on parallel terms compatible with the composition; this compatibility can be split in two parts: substitution and replacement. In addition, the associativity and identity axioms hold up to congruence. These properties of the monadic equational theories can be described by a set of inference rules, as in Figure 1.

![Figure 1: Rules of the monadic equational logic](image)

Adding products to the monadic equational logic. In contrast with equational theories, the existence of products is not required in a monadic equational theory. However some specific products may exist. A product in a monadic equational theory \( \mathbf{T} \) is “up to congruence”, in the following sense. Let \( (Y_i)_{i \in I} \) be a family of objects in \( \mathbf{T} \), indexed by some set \( I \). A product with base \( (Y_i)_{i \in I} \) is a cone \( (q_i : Y \to Y_i)_{i \in I} \) such that for every cone \( (f_i : X \to Y_i)_{i \in I} \) on the same base there is a term \( \langle f_i \rangle_{i \in I} : X \to Y \) such that \( q_i \circ f_i \equiv f_i \) for each \( i \), and in addition this term is unique up to congruence, in the sense that if \( f, g : X \to Y \) are such that \( q_i \circ f \equiv q_i \circ g \) for each \( i \) then \( f \equiv g \). When \( I \) is empty, we get a terminal object \( \bot \), such that for every \( X \) there is an arrow \( \langle \_ \rangle : X \to \bot \) which is unique up to congruence. The corresponding inference rules are given in Figure 2. The quantification “\( \forall i \)”, or “\( \forall i \in I \)”, is a kind of “syntactic sugar”: when occurring in the premisses of a rule it stands for a conjunction of premisses.

2 Three logics for states

In this section we introduce three logics for dealing with states as computational effects. This generalizes the example of the bank account in Section 1.2. We present first the explicit logic (close to the semantics), then the apparent logic (close to the syntax), and finally the decorated logic and the morphisms from the decorated logic to the apparent and the explicit ones. In the syntax of an imperative language there is no type of states (the state is “hidden”) while the interpretation of this language involves a set of states \( St \). More precisely, if the types \( X \) and \( Y \) are interpreted as the sets \( \{X\} \) and \( \{Y\} \), then each term \( f : X \to Y \) is interpreted as a function \( \llbracket f \rrbracket : \{X\} \times St \to \{Y\} \times St \). In Moggi’s paper introducing monads for effects [Moggi 1991] such a term \( f : X \to Y \) is called a computation, and whenever the function \( \llbracket f \rrbracket \) is \( \llbracket f \rrbracket_0 \times \text{id}_{St} \) for some \( \llbracket f \rrbracket_0 : \{X\} \to \{Y\} \) then \( f \) is called a value. We keep this distinction, using modifier and pure.
Let us define the explicit theory for states

Set of states $\text{St}$ with the syntax. The explicit theory for states

2.1 The explicit logic for states

The explicit logic for states $\mathcal{L}_{\text{expl}}$ is a kind of “pointed” monadic equational logic: a theory $\Theta_{\text{expl}}$ for $\mathcal{L}_{\text{expl}}$ is a monadic equational theory with a distinguished object $S$, called the type of states, and with a product-with-$S$ functor $X \times S$. As in Section 1.2, the explicit logic provides the relevant semantics, but it is far from the syntax. The explicit theory for states $\text{State}_{\text{expl}}$ is generated by a type $V_i$ and an operation $l_{i,1} : S \rightarrow V_i$ for each location $i$, which form a product $l_{i,1} : S \rightarrow V_i \in \text{Loc}$. Thus, for each location $i$ there is an operation $u_i : V_i \times S \rightarrow S$, unique up to congruence, which satisfies the equations below (where $p_i : V_i \times S \rightarrow V_i$ and $q_i : V_i \times S \rightarrow S$ are the projections):

\[
\text{State}_{\text{expl}} : \begin{cases}
\text{operations} & l_{i,1} : S \rightarrow V_i, \ u_i : V_i \times S \rightarrow S \\
\text{products} & (l_{i,1} : S \rightarrow V_i)_{i \in \text{Loc}} \\
\text{equations} & l_{i,1} \circ u_i \equiv p_i : V_i \times S \rightarrow V_i, \ l_{j,1} \circ u_i \equiv l_{j,1} \circ q_i : V_i \times S \rightarrow V_j \quad \text{for each } j \neq i
\end{cases}
\]

Let us define the explicit theory $\text{Set}_{\text{expl}}$ as the category of sets with the equality as congruence and with the set of states $\text{St} = \prod_{i \in \text{Loc}} \text{Val}_i$ as its distinguished set. The semantics of states, as described in Section 1.1, is the model $M_{\text{expl}} : \text{State}_{\text{expl}} \rightarrow \text{Set}_{\text{expl}}$ which maps the type $V_i$ to the set $\text{Val}_i$ for each $i \in \text{Loc}$, the type $S$ to the set $\text{St}$, and the operations $l_{i,1}$ and $u_i$ to the functions $\text{lookup}_{i,1}$ and $\text{update}_i$, respectively.

2.2 The apparent logic for states

The apparent logic for states $\mathcal{L}_{\text{app}}$ is the monadic equational logic (Section 1.3). As in Section 1.2, the apparent logic is close to the syntax but it does not provide the relevant semantics. The apparent theory for
states \( \text{State}_{\text{app}} \) can be obtained from the explicit theory \( \text{State}_{\text{expl}} \) by identifying the type of states \( S \) with the unit type \( 1 \). So, there is in \( \text{State}_{\text{app}} \) a terminal type \( 1 \) and for each location \( i \) a type \( V_i \) for the possible values of \( i \) and an operation \( l_i : 1 \rightarrow V_i \) for observing the value of \( i \). A set-valued model for this part of \( \text{State}_{\text{app}} \), with the constraint that for each \( i \) the interpretation of \( V_i \) is the given set \( \text{Val}_i \), is made of an element \( a_i \in \text{Val}_i \) for each \( i \) (it is the image of the interpretation of \( l_i \)). Thus, such a model corresponds to a state, made of a value for each location; this is known as the states-as-models or states-as-algebras point of view [Gaudel et al., 1990]. In addition, it is assumed that in \( \text{State}_{\text{app}} \) the operations \( l_i \)'s form a product \( (l_i : 1 \rightarrow V_i)_{i \in \text{Loc}} \). This assumption implies that each \( l_i \) is an isomorphism, so that each \( V_i \) must be interpreted as a singleton: this does not fit with the semantics of states. However, we will see in Section 2.3 that this assumption becomes meaningful when decorations are added, in a similar way as in the bank example in Section 1.2. Formally, the assumption that \( (l_i : 1 \rightarrow V_i)_{i \in \text{Loc}} \) is a product provides for each location \( i \) an operation \( u_i : V_i \rightarrow 1 \), unique up to congruence, which satisfies the equations below (where \( id_i : V_i \rightarrow V_i \) is the identity and \( \langle \rangle_i = \langle \rangle_{V_i} : V_i \rightarrow 1 \)):

\[
\text{State}_{\text{app}} : \begin{cases}
\text{operations} & l_i : 1 \rightarrow V_i \ , \ u_i : V_i \rightarrow 1 \\
\text{product} & (l_i : 1 \rightarrow V_i)_{i \in \text{Loc}} \text{ with terminal type } 1 \\
\text{equations} & l_i \circ u_i \equiv id_i : V_i \rightarrow V_i \ , \ l_j \circ u_i \equiv l_j \circ \langle \rangle_i : V_i \rightarrow V_j \text{ for each } j \neq i
\end{cases}
\]

At first view, these equations mean that after \( u_i(a) \) is executed, the value of \( i \) is put to \( a \) and the value of \( j \) (for \( j \neq i \)) is unchanged. However, as noted above, this intuition is not supported by the semantics in the apparent logic. We will see in Section 2.3 that these equations become sound when relevant decorations are added, so that the apparent logic can be used for checking the validity of a decorated proof, as explained in Section 2.4.

### 2.3 The decorated logic for states

Now, as in Section 1.2, we introduce a third logic for states, which is close to the syntax and which provides the relevant semantics. It is defined by adding “decorations” to the apparent logic. A theory \( \Theta_{\text{deco}} \) for the decorated logic for states \( L_{\text{deco}} \) is made of:

- A monadic equational theory \( \Theta^{(2)} \). The terms in \( \Theta^{(2)} \) may be called the modifiers and the equations \( f \equiv g \) may be called the strong equations.

- Two additional monadic equational theories \( \Theta^{(0)} \) and \( \Theta^{(1)} \), with the same types as \( \Theta^{(2)} \), and such that \( \Theta^{(0)} \subseteq \Theta^{(1)} \subseteq \Theta^{(2)} \) and the congruence on \( \Theta^{(0)} \) and on \( \Theta^{(1)} \) is the restriction of the congruence on \( \Theta^{(2)} \). The terms in \( \Theta^{(1)} \) may be called the accessors, and if they are in \( \Theta^{(0)} \) they may be called the pure terms.

- A second equivalence relation \( \sim \) between parallel terms in \( \Theta^{(2)} \), which is only “weakly” compatible with the composition; the relation \( \sim \) satisfies the substitution property but only a weak version of the replacement property, called the pure replacement: if \( f_1 \sim f_2 : X \rightarrow Y \) and \( g : Y \rightarrow Z \) then in general \( g \circ f_1 \not\sim g \circ f_2 \), except when \( g \) is pure. The relations \( f \sim g \) are called the weak equations. It is assumed that every strong equation is a weak equation and that every weak equation between accessors is a strong equation, so that the relations \( \equiv \) and \( \sim \) coincide on \( \Theta^{(0)} \) and on \( \Theta^{(1)} \).

We use the following notations, called decorations: a pure term \( f \) is denoted \( f^{(0)} \), an accessor \( f \) is denoted \( f^{(1)} \), and a modifier \( f \) is denoted \( f^{(2)} \); this last decoration is unnecessary since every term is a modifier, however it may be used for emphasizing. Figure 3 provides the decorated rules, which describe the properties of the decorated theories. For readability, the decoration properties may be grouped with other properties: for instance, “\( f^{(1)} \sim g^{(1)} \)” means “\( f^{(1)} \) and \( g^{(1)} \) and \( f \sim g \).”

Some specific kinds of products may be used in a decorated theory, for instance:

- A distinguished type \( 1 \) with the following decorated terminality property: for each type \( X \) there is a pure term \( \langle \rangle_X : X \rightarrow 1 \) such that every modifier \( g : X \rightarrow 1 \) satisfies \( g \sim \langle \rangle_X \). It follows from the properties of weak equations that \( 1 \) is a terminal type in \( \Theta^{(0)} \) and in \( \Theta^{(1)} \).
A decorated theory of sets consists of a set of operations (including projections, accessor functions, and so on) on decorated types. For each set, a modifier is defined that allows us to prove strong equations from weak ones. This is achieved by looking at the results of some observations, thanks to the properties of the observational product.

**Rules of the monadic equational logic, and:**

\[
\begin{align*}
(0\text{-id}) & \quad \frac{X}{id_X^{(0)} : X \to X} \\
(0\text{-comp}) & \quad \frac{f^{(0)} g^{(0)}}{(g \circ f)^{(0)}} \\
(0\text{-to-1}) & \quad \frac{f^{(0)}}{f^{(1)}} \\
(1\text{-comp}) & \quad \frac{f^{(1)} g^{(1)}}{(g \circ f)^{(1)}} \\
(1\text{-to-0}) & \quad \frac{f^{(1)} \sim g^{(1)}}{f \equiv g} \\
(\equiv\text{-to-}) & \quad \frac{f \equiv g}{f \sim g} \\
(\sim\text{-refl}) & \quad \frac{f \sim f}{f \sim g} \\
(\sim\text{-sym}) & \quad \frac{f \sim g}{g \sim f} \\
(\sim\text{-trans}) & \quad \frac{f \sim g}{g \sim h} \quad \frac{g \sim h}{f \sim h} \\
\sim\text{-subs} & \quad \frac{f : X \to Y}{g_1 \sim g_2 : Y \to Z} \\
& \quad \frac{g_1 \circ f \sim g_2 \circ f : X \to Z}{g \circ f_1 \sim g \circ f_2 : X \to Z}
\end{align*}
\]

**Figure 3:** Rules of the decorated logic for states

- An observational product with base \((Y_i)_{i \in I}\) is a cone of accessors \((q_i : Y \to Y_i)_{i \in I}\) such that for every cone of accessors \((f_i : X \to Y_i)_{i \in I}\) on the same base there is a modifier \(\langle f_i \rangle_{i \in I} : X \to Y\) such that \(q_i \circ f_i \sim f_i\) for each \(i\), and in addition this modifier is unique up to strong equations, in the sense that if \(f, g : X \to Y\) are modifiers such that \(q_i \circ f \sim q_i \circ g\) for each \(i\) then \(f \equiv g\). An observational product allows to prove strong equations from weak ones: by looking at the results of some observations, thanks to the properties of the observational product, we get information on the state.

**Figure 4:** Rules for some decorated products for states

When \(\mathbb{1}\) is a decorated terminal type:

\[
\begin{align*}
(0\text{-final}) & \quad \frac{X}{\langle (\mathbb{1}) \rangle_X^{(0)} : X \to \mathbb{1}} \\
(\sim\text{-final-unique}) & \quad \frac{f, g : X \to \mathbb{1}}{f \sim g}
\end{align*}
\]

When \((q_i^{(1)} : Y \to Y_i)_{i \in I}\) is an observational product:

\[
\begin{align*}
(\text{obs-tuple}) & \quad \frac{\langle f_i^{(1)} \rangle_{i \in I} : X \to Y_i}{}
\end{align*}
\]

\[
\begin{align*}
(\text{obs-tuple-proj-i}) & \quad \frac{\langle j_i^{(1)} \rangle_{j \in I}}{q_i \circ \langle j_i \rangle \sim j_i}
\end{align*}
\]

\[
\begin{align*}
(\text{obs-tuple-unique}) & \quad \frac{\langle f_i^{(2)} \rangle_{i \in I} : X \to Y \forall i q_i \circ f \sim q_i \circ g}{f \equiv g}
\end{align*}
\]

The decorated theory of states \(\text{State}_{\text{deco}}\) is generated by a type \(V_i\) and an accessor \(l_i^{(1)} : \mathbb{1} \to V_i\) for each \(i \in \text{Loc}\), which form an observational product \((l_i^{(1)} : \mathbb{1} \to V_i)_{i \in \text{Loc}}\). The modifiers \(u_i\)'s are defined (up to strong equations), using the property of the observational product, by the weak equations below:

\[
\begin{align*}
\text{State}_{\text{deco}} : & \quad \left\{ \begin{array}{l}
\text{operations} \quad \langle l_i^{(1)} \rangle : \mathbb{1} \to V_i, \quad u_i^{(2)} : V_i \to \mathbb{1} \\
\text{observational product} \quad \langle l_i^{(1)} \rangle : \mathbb{1} \to V_i_{\text{Loc}} \quad \text{with decorated terminal type} \mathbb{1} \\
\text{equations} \quad l_i \circ u_i \sim id_i : V_i \to V_i, \quad l_j \circ u_i \sim l_j \circ \langle j \rangle : V_i \to V_j \quad \text{for each} \quad j \neq i
\end{array} \right.
\end{align*}
\]

The decorated theory of sets \(\text{Set}_{\text{deco}}\) is built from the category of sets, as follows. There is in \(\text{Set}_{\text{deco}}\) a type for each set, a modifier \(f^{(0)} : X \to Y\) for each function \(f : X \times St \to Y \times St\), an accessor \(f^{(1)} : X \to Y\) for each function \(f : X \to Y\).
for each function \( f : X \times St \to Y \), and a pure term \( f^{(0)} : X \to Y \) for each function \( f : X \to Y \), with the straightforward conversions. Let \( f^{(2)}, g^{(2)} : X \to Y \) corresponding to \( f, g : X \times St \to Y \times St \). A strong equation \( f \equiv g \) is an equality \( f = g : X \times St \to Y \times St \), while a weak equation \( f \sim g \) is an equality \( p \circ f = p \circ g : X \times St \to Y \), where \( p : Y \times St \to Y \) is the projection. For each location \( i \) the projection \( \text{lookup}_i : St \to \text{Val}_i \) corresponds to an accessor \( \text{lookup}_i^{(1)} : 1 \to \text{Val}_i \) in \( \text{Set}_{\text{deco}} \), so that the family \( \{ \text{lookup}_i^{(1)} \}_{i \in \text{Loc}} \) forms an observational product in \( \text{Set}_{\text{deco}} \). We get a model \( M_{\text{deco}} \) of \( \text{State}_{\text{deco}} \) with values in \( \text{Set}_{\text{deco}} \) by mapping the type \( \text{V}_i \) to the set \( \text{Val}_i \) and the accessor \( i^{(1)} \) to the accessor \( \text{lookup}_i^{(1)} \), for each \( i \in \text{Loc} \). Then for each \( i \) the modifier \( \text{update}_i^{(2)} \) is mapped to the modifier \( \text{update}_i^{(2)} \).

### 2.4 From decorated to apparent

Every decorated theory \( \Theta_{\text{deco}} \) gives rise to an apparent theory \( \Theta_{\text{app}} \) by dropping the decorations, which means that the apparent theory \( \Theta_{\text{app}} \) is made of a type \( X \) for each type \( X \) in \( \Theta_{\text{deco}} \), a term \( f : X \to Y \) for each modifier \( f : X \to Y \) in \( \Theta_{\text{deco}} \) (which includes the accessors and the pure terms), and an equation \( f \equiv g \) for each weak equation \( f \sim g \) in \( \Theta_{\text{deco}} \) (which includes the strong equations). Thus, the distinction between modifiers, accessors and pure terms disappears, as well as the distinction between weak and strong equations. Equivalently, the apparent theory \( \Theta_{\text{app}} \) can be defined as the apparent theory \( \Theta^{(2)} \) together with an equation \( f \equiv g \) for each weak equation \( f \sim g \) in \( \Theta_{\text{deco}} \) which is not associated to a strong equation in \( \Theta_{\text{deco}} \) (otherwise, it is yet in \( \Theta^{(2)} \)). Thus, a decorated terminal type in \( \Theta_{\text{deco}} \) becomes a terminal type in \( \Theta_{\text{app}} \) and an observational product \( (q_i^{(1)} : Y \to Y_i)_i \) in \( \Theta_{\text{deco}} \) becomes a product \( (q_i : Y \to Y_i)_i \) in \( \Theta_{\text{app}} \).

In the same way, each rule of the decorated logic is mapped to a rule of the apparent logic by dropping the decorations. This property can be used for checking a decorated proof in two steps, by checking on one side the undecorated proof and on the other side the decorations. This construction of \( \Theta_{\text{app}} \) from \( \Theta_{\text{deco}} \) by dropping the decorations, is a morphism from \( \mathcal{L}_{\text{deco}} \) to \( \mathcal{L}_{\text{app}} \), denoted \( F_{\text{app}} \).

### 2.5 From decorated to explicit

Every decorated theory \( \Theta_{\text{deco}} \) gives rise to an explicit theory \( \Theta_{\text{expl}} \) by expanding the decorations, which means that the explicit theory \( \Theta_{\text{expl}} \) is made of:

- A type \( X \) for each type \( X \) in \( \Theta_{\text{deco}} \); projections are denoted by \( p_X : X \times S \to X \) and \( q_X : X \times S \to S \).
- A term \( f_2 : X \times S \to Y \times S \) for each modifier \( f : X \to Y \) in \( \Theta_{\text{deco}} \), such that:
  - if \( f \) is an accessor then there is a term \( f_1 : X \times S \to Y \) in \( \Theta_{\text{expl}} \) such that \( f_2 = \langle f_1, q_X \rangle \),
  - if moreover \( f \) is a pure term then there is a term \( f_0 : X \to Y \) in \( \Theta_{\text{expl}} \) such that \( f_1 = f_0 \circ p_X \), hence \( f_2 = \langle f_0 \circ p_X, q_X \rangle = f_0 \circ id_S \) in \( \Theta_{\text{expl}} \).
- An equation \( f_2 \equiv g_2 : X \times S \to Y \times S \) for each strong equation \( f \equiv g \) : \( X \to Y \) in \( \Theta_{\text{deco}} \).
- An equation \( p_Y \circ f_2 \equiv p_Y \circ g_2 : X \times S \to Y \) for each weak equation \( f \sim g : X \to Y \) in \( \Theta_{\text{deco}} \).
- A product \( (q_{i,1} : Y \times S \to Y_i)_i \) for each observational product \( (q_i^{(1)} : Y \to Y_i)_i \) in \( \Theta_{\text{deco}} \).

This construction of \( \Theta_{\text{expl}} \) from \( \Theta_{\text{deco}} \) is a morphism from \( \mathcal{L}_{\text{deco}} \) to \( \mathcal{L}_{\text{expl}} \), denoted \( F_{\text{expl}} \) and called the expansion. The expansion morphism makes explicit the meaning of the decorations, by introducing a “type of states” \( S \). Thus, each modifier \( f \) gives rise to a term \( f_2 \) which may use and modify the state, while whenever \( f \) is an accessor then \( f_2 \) may use the state but is not allowed to modify it, and when moreover \( f \) is pure then \( f_2 \) may neither use nor modify the state. When \( f \equiv g \) then \( f_2 \) and \( g_2 \) must return the same result and the same state; when \( f \sim g \) then \( f_2 \) and \( g_2 \) must return the same result but maybe not the same state. We have seen that the semantics of states cannot be described in the apparent logic, but can be described both in the decorated logic and in the explicit logic. It should be reminded that every morphism of logics is a left adjoint functor. This is the case for the expansion morphism \( F_{\text{expl}} : \mathcal{L}_{\text{deco}} \to \mathcal{L}_{\text{expl}} \): it
is a left adjoint functor $F_{\text{expl}} : T_{\text{deco}} \to T_{\text{expl}}$, its right adjoint is denoted $G_{\text{expl}}$. In fact, it is easy to check that $\text{Set}_{\text{deco}} = G_{\text{expl}}(\text{Set}_{\text{expl}})$, and since $\text{State}_{\text{expl}} = F_{\text{expl}}(\text{State}_{\text{deco}})$ it follows that the decorated model $M_{\text{deco}} : \text{State}_{\text{deco}} \to \text{Set}_{\text{deco}}$ and the explicit model $M_{\text{expl}} : \text{State}_{\text{expl}} \to \text{Set}_{\text{expl}}$ are related by the adjunction $F_{\text{expl}} \dashv G_{\text{expl}}$. This means that the models $M_{\text{deco}}$ and $M_{\text{expl}}$ are two different ways to formalize the semantics of states from Section 1.1. In order to conclude Section 2 the morphims of logic $F_{\text{app}}$ and $F_{\text{expl}}$ are summarized in Figure 5.

| $\Theta_{\text{app}}$ | $F_{\text{app}}$ | $\Theta_{\text{deco}}$ | $F_{\text{expl}}$ | $\Theta_{\text{expl}}$ |
|------------------------|------------------|------------------------|------------------|------------------------|
| $f : X \to Y$          | modifier         | $f^{(2)} : X \to Y$    | $f_2 : X \times S \to Y \times S$ |
| $f : X \to Y$          | accessor         | $f^{(1)} : X \to Y$    | $f_1 : X \times S \to Y$      |
| $f : X \to Y$          | pure term        | $f^{(0)} : X \to Y$    | $f_0 : X \to Y$               |
| $f \equiv g : X \to Y$ | strong equation  | $f \equiv g : X \to Y$ | $f_2 \equiv g_2 : X \times S \to Y \times S$ |
| $f \equiv g : X \to Y$ | weak equation    | $f \sim g : X \to Y$   | $p_Y \circ f_2 \equiv p_Y \circ g_2 : X \times S \to Y$ |

Figure 5: A span of logics for states

### 3 Decorated proofs

The inference rules of the decorated logic $L_{\text{deco}}$ are now used for proving some of the Equations (2) (in Remark 1.1). All proofs in this section are performed in the decorated logic; for readability the identity and associativity rules (id-src), (id-tgt) and (assoc) are omitted. Some derived rules are proved in Section 3.1, then Equation (2.1) is proved in Section 3.2. In order to deal with the equations with two values as argument or as result, we use the semi-pure products introduced in [Dumas et al. 2011a]; the rules for semi-pure products are reminded in Section 3.3, then all seven Equations (2) are expressed in the decorated logic and Equation (2.6) is proved in Section 3.4. Proving the other equations would be similar. We use as axioms the fact that $l_i$ is an accessor and the weak equations in $\text{State}_{\text{deco}}$ (Section 2.3).

#### 3.1 Some derived rules

Let us now derive some rules from the rules of the decorated logic (Figures 3 and 4).

\[
\begin{align*}
(E_1^{(1)}) & \quad \frac{f^{(1)} : X \to \bar{n}}{f \equiv g} \\
(E_2^{(1)}) & \quad \frac{f^{(1)} : X \to \bar{n}}{f \equiv \langle x \rangle}
\end{align*}
\]

\[
\begin{align*}
(E_3^{(1)}) & \quad \frac{f^{(1)} : X \to Y \quad g^{(1)} : Y \to \bar{n} \quad h^{(1)} : X \to \bar{n}}{g \circ f \equiv h} \\
(E_4^{(1)}) & \quad \frac{f^{(1)} : \bar{n} \to X \quad \langle x \circ f \equiv \text{id}_a \rangle}{\langle x \circ f \equiv \text{id}_a \rangle}
\end{align*}
\]

\[
\begin{align*}
(E_1^{(0)}) & \quad \frac{f^{(0)} : X \to \bar{n} \quad g^{(0)} : X \to \bar{n}}{f \equiv g} \\
(E_2^{(0)}) & \quad \frac{f^{(0)} : X \to \bar{n}}{f \equiv \langle x \rangle}
\end{align*}
\]

\[
\begin{align*}
(E_3^{(0)}) & \quad \frac{f^{(0)} : X \to Y \quad g^{(0)} : Y \to \bar{n} \quad h^{(0)} : X \to \bar{n}}{g \circ f \equiv h} \\
(E_4^{(0)}) & \quad \frac{f^{(0)} : \bar{n} \to X \quad \langle x \circ f \equiv \text{id}_a \rangle}{\langle x \circ f \equiv \text{id}_a \rangle}
\end{align*}
\]

Figure 6: Some derived rules in the decorated logic for states

**Proof.** The derived rules in the left part of Figure 6 can be proved as follows. The proof of the rules in the right part are left to the reader.

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In this section we prove the decorated equation $u_i^{(2)} \circ l_i^{(1)} \equiv \text{id}_{\emptyset}^{(0)}$. It is easy to check that this decorated equation gets expanded as $u_i \circ l_i \equiv \text{id}_{S}$, which clearly gets interpreted as Equation (2.1) in Remark 1.1. This decorated equation is now proved using the axioms of State$^{\text{deco}}$ in Section 2.3; for each location $i$:

\((A_0)\) $l_i^{(1)}$, \hspace{1cm} \((A_1)\) $l_i \circ u_i \sim \text{id}_{i}$, \hspace{1cm} \((A_2)\) $l_j \circ u_i \sim l_j \circ \langle \rangle_i$ for each $j \neq i$.

**Proposition 3.1.** For each location $i$, reading the value of a location $i$ and then updating the location $i$ with the obtained value is just like doing nothing.

$u_i^{(2)} \circ l_i^{(1)} \equiv \text{id}_{\emptyset}^{(0)} : \emptyset \rightarrow \emptyset$.

**Proof.** Let $i$ be a location. Using the unicity property of the observational product (rule (obs-tuple-unique) in Figure 4), we have to prove that $l_k \circ u_i \circ l_i \sim l_k : \emptyset \rightarrow \emptyset$ for each location $k$.

- When $k = i$, the substitution rule for $\sim$ yields:

\[(\sim\text{-subs}) \hspace{1cm} (A_1) \hspace{0.5cm} l_i \circ u_i \sim \text{id}_i \hspace{0.5cm} l_i \circ u_i \sim l_i\]

- When $k \neq i$, using the substitution rule for $\sim$ and the replacement rule for $\equiv$ we get:

\[\begin{align*}
\text{(\sim}\text{-repl}) & \hspace{1cm} \langle \rangle_i \circ l_i \equiv \text{id}_{\emptyset} \\
\text{(\equiv\text{-to-}\sim}) & \hspace{1cm} l_k \circ \langle \rangle_i \circ l_i \equiv l_k \\
\text{(\sim}\text{-trans}) & \hspace{1cm} l_k \circ u_i \circ l_i \sim l_k \circ \langle \rangle_i \circ l_i \sim l_k
\end{align*}\]
3.3 Semi-pure products

Let $\Theta_{\text{deco}}$ be a theory with respect to the decorated logic for states and let $\Theta^{(0)}$ be its pure part, so that $\Theta^{(0)}$ is a monadic equational theory. The product of two types $X_1$ and $X_2$ in $\Theta_{\text{deco}}$ is defined as their product in $\Theta^{(0)}$ (it is a product up to strong equations, as in Section 1.1). The projections from $X_1 \times X_2$ to $X_1$ and $X_2$ are respectively denoted by $\pi_1^{(0)}$ and $\pi_2^{(0)}$ (the types $X_1$ and $X_2$ will always be clear from the context). The product of two pure morphisms $f_1^{(0)} : X_1 \to Y_1$ and $f_2^{(0)} : X_2 \to Y_2$ is a pure morphism $(f_1 \times f_2)^{(0)} : X_1 \times X_2 \to Y_1 \times Y_2$ subject to the rules in Figure 7, which are the usual rules for products up to strong equations. Moreover when $X_1$ or $X_2$ is $\bot$ it can be proved in the usual way that the projections $\pi_1^{(0)} : X_1 \times \bot \to X_1$ and $\pi_2^{(0)} : \bot \times X_2 \to X_2$ are isomorphisms. The permutation $\text{perm}_{X_1,X_2}^{(0)} : X_1 \times X_2 \to X_2 \times X_1$ is defined as usual by $\pi_1 \circ \text{perm}_{X_1,X_2} \equiv \pi_2$ and $\pi_2 \circ \text{perm}_{X_1,X_2} \equiv \pi_1$.

![Figure 7: Rules for products of pure morphisms](image)

The rules in Figure 7, which are symmetric in $f_1$ and $f_2$, cannot be applied to modifiers: indeed, the effect of building a pair of modifiers depends on the evaluation strategy. However, following [Dumas et al. 2011a], we define the left semi-pure product of an identity $\text{id}_X$ and a modifier $f : X_2 \to Y_2$, as a modifier $\text{id}_X \times f : X \times X_2 \to X \times Y_2$ subject to the rules in Figure 8, which form a decorated version of the rules for products. Symmetrically, the right semi-pure product of a modifier $f : X_1 \to Y_1$ and an identity $\text{id}_X$ is a modifier $f \times \text{id}_X : X_1 \times X \to Y_1 \times X$ subject to the rules symmetric to those in Figure 8.

![Figure 8: Rules for left semi-pure products](image)

Let us add the rules for semi-pure products to the decorated logic for states. In the decorated theory of states $\text{State}_{\text{deco}}$, let us assume that there are products $V_i \times V_j$ and $\bot \times \bot$ for all locations $i$ and $j$. Then it is easy to check that the expansion of the decorated Equations (2) below gets interpreted as Equations (2) in Remark 1.1. We use the simplified notations $\text{id}_i = \text{id}_{V_i}$ and $\langle \rangle_i = \langle \rangle_{V_i}$ and $\text{perm}_{i,j} = \text{perm}_{V_i,V_j}$. Equation (2.1) has been proved in Section 3.2 and Equation (2.6) will be proved in Section 3.3.

The other equations can be proved in a similar way.

(2.1) **Annihilation lookup-update.** $\forall i \in \text{Loc}, \ u_i \circ l_i \equiv \text{id}_\bot : \bot \to \bot$
(2.2) Interaction lookup-update. \( \forall i \in \text{Loc}, l_i \circ \langle \rangle_i \circ l_i \equiv l_i : \mathbb{I} \rightarrow V_i \)

(2.3) Interaction update-update. \( \forall i \in \text{Loc}, u_i \circ \pi_2 \circ (u_i \times i_{d_i}) \equiv u_i \circ \pi_2 : V_i \times V_i \rightarrow \mathbb{I} \)

(2.4) Interaction update-update. \( \forall i \in \text{Loc}, l_i \circ u_i \sim i_{d_i} : V_i \rightarrow V_i \)

(2.5) Commutation lookup-update. \( \forall i \neq j \in \text{Loc}, l_j \circ \langle \rangle_j \circ l_i \equiv \text{perm}_{j,i} \circ l_i \circ \langle \rangle_j \circ l_j : \mathbb{I} \rightarrow V_i \times V_j \)

(2.6) Commutation update-update. \( \forall i \neq j \in \text{Loc}, u_j \circ \pi_2 \circ (u_i \times i_{d_j}) \equiv u_i \circ \pi_1 \circ (i_{d_i} \times u_j) : V_i \times V_j \rightarrow \mathbb{I} \)

(2.7) Commutation update-update. \( \forall i \neq j \in \text{Loc}, l_j \circ u_i \equiv \pi_2 \circ (i_{d_i} \times l_j) \circ (u_i \times i_{d_j}) \circ \pi_1^{-1} : V_i \rightarrow V_j \)

3.4 Commutation update-update

Proposition 3.2. For each locations \( i \neq j \), the order of storing in two different locations \( i \) and \( j \) does not matter.

\[ u_j^{(2)} \circ \pi_2^{(0)} \circ (u_i \times i_{d_j})^{(2)} \equiv u_i^{(2)} \circ \pi_1^{(0)} \circ (i_{d_i} \times u_j)^{(2)} : V_i \times V_j \rightarrow \mathbb{I} . \]

Proof. Let \( i \) and \( j \) be two distinct locations. Using the unicity property of the observational product (rule (obs-tuple-unique) in Figure 4), we have to prove that \( l_k \circ u_j \circ \pi_2 \circ (u_i \times i_{d_j}) \sim l_k \circ u_i \circ \pi_1 \circ (i_{d_i} \times u_j) \) for each location \( k \).

- When \( k \neq i, j \), let us prove independently four weak equations (W1) to (W4):

\[ (A_2) \quad l_k \circ u_j \sim l_k \circ \langle \rangle_j \]

\[ (A_2) \quad l_k \circ u_j \circ \pi_2 \circ (u_i \times i_{d_j}) \sim l_k \circ \langle \rangle_j \circ \pi_2 \circ (u_i \times i_{d_j}) \]

\[ (\equiv \text{-subs}) \quad \frac{\pi_2 \equiv \pi_1}{l_k \circ u_j \circ \pi_2 \circ (u_i \times i_{d_j}) \equiv l_k \circ \langle \rangle_j \circ \pi_2 \circ (u_i \times i_{d_j})} \]

\[ (\equiv \text{-trans}) \quad \frac{(\equiv \text{-trans})}{l_k \circ \langle \rangle_j \circ \pi_2 \circ (u_i \times i_{d_j}) \sim l_k \circ u_i \circ \pi_1} \]

Equations (W1) to (W4) together with the transitivity rule for \( \sim \) give rise to the weak equation:

\[ l_k \circ u_j \circ \pi_2 \circ (u_i \times i_{d_j}) \sim l_k \circ \langle \rangle_{V_i \times V_j} \]

A symmetric proof shows that \( l_k \circ u_i \circ \pi_1 \circ (i_{d_i} \times u_j) \sim l_k \circ \langle \rangle_{V_i \times V_j} \). With the symmetry and transitivity rules for \( \sim \), this concludes the proof when \( k \neq i, j \).

- When \( k = i \), on the one hand it is easy to prove that \( l_i \circ u_i \circ \pi_1 \circ (i_{d_i} \times u_j) \sim \pi_1 \), as follows.

\[ (\equiv \text{-subs}) \quad \frac{\langle \rangle_i \circ \pi_1 \equiv \langle \rangle_{V_i \times V_j}}{l_i \circ \langle \rangle_i \circ \pi_1 \equiv \langle \rangle_{V_i \times V_j}} \]

On the other hand it can also be proved that \( l_i \circ u_j \circ \pi_2 \circ (u_i \times i_{d_j}) \sim \pi_1 \), as follows.
Equations \((W'_1)\) to \((W'_3)\) and the transitivity rule for \(\sim\) give rise to \(l_i \circ u_j \circ \pi_2 \circ (u_i \times id_j) \sim \pi_1\). With the symmetry and transitivity rules for \(\sim\), this concludes the proof when \(k = i\).

- The proof when \(k = j\) is symmetric to the proof when \(k = i\).

\[\square\]

**Conclusion**

In this paper, decorated proofs are used for proving properties of states. This can be applied to other computational effects, like exceptions [Dumas et al. 2011b]. In addition, associating to each effect a span of logics as in Section 2 should result in a simple framework for combining effects.

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