

Towards Certified Management of Financial Contracts*

Patrick Bahr, Jost Berthold and Martin Elsman

University of Copenhagen
Dept. of Computer Science (DIKU)
{paba,berthold,mael}@di.ku.dk

1 Introduction

Banks and financial institutions nowadays often use domain-specific languages (DSLs) for describing complex financial contracts, in particular, for specifying how asset transfers for a specific contract depend on underlying observables, such as interest rates and stock prices.

The seminal work by Peyton-Jones, Eber, and Seward on financial contracts [7] shows how an algebraic approach to contract specification can be used for valuation of contracts (when combined with a model of the underlying observables) and for managing how contracts evolve under so-called fixings¹ and decision-taking, with the contracts eventually evaporating into the empty contract, for which no party has further obligations. The ideas have emerged into Eber’s company *LexiFi*, which has become a leading software provider for a range of financial institutions, with all contract management operations centralised around a domain-specific contract language hosted in MLFi [5], a derivative of the functional programming language OCaml.

In this paper, we present a small simple contract language, which rigorously relegates any artefacts of modelling and computation from its core. The language shares the same vision as the previously mentioned work with the addition that it (a) allows for specifying multi-party contracts [1], such as entire portfolios, (b) has good algebraic properties, well suited for formal and verified reasoning, and yet (c) allows for expressing many interesting contracts appearing in real-world portfolios, such as various variations of so-called barrier

options. We show that plenty of information can be derived from, and useful manipulations defined on, just the symbolic contract specification, independent of any stochastic aspects of the modelled contracts. Contracts modelled in our language are analysed and transformed for management according to a precise cash-flow semantics, modelled and checked using the Coq proof assistant. Implementations in Haskell and Coq are available online² together with machine-checkable proofs (in Coq) of the key properties of the contract language.

2 The Contract Language

Financial contracts essentially define future transactions (*cash-flows*) between different parties who agree on a contract. Amounts in contracts may be *scaled* using a real-valued expression ($\text{Expr}_{\mathbb{R}}$), which may refer to *observable* underlying values, such as foreign exchange rates, stock prices, or market indexes. Likewise, contracts can contain *alternatives* depending on Boolean predicates ($\text{Expr}_{\mathbb{B}}$), which may refer to observables, as well as external *decisions* taken by the parties involved.

Observables and choices in our contract language are “observed” with a given offset from the current day. In general, all definitions use *relative time*, aiding the compositionality of contracts.

A common contract structure is to *repeat* a choice between alternatives until a given end date. As a simple example, consider an *FX option* on US dollars: Party X may, within 90 days, decide to buy USD 100 for a fixed rate r of Danish Kroner from Party Y:

```
option = checkWithin(chosenBy(X, 0), 90, trade, zero)
trade = scale(100, both(transfer(Y, X, USD), pay))
pay = scale(r, transfer(X, Y, DKK))
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¹Underlying observables gradually become fixed when time passes by.

²See <https://github.com/HIPERFIT/contracts>.

The *checkWithin* construct generalises an alternative by iterating the decision (*chosenBy*) of party X. If X chooses at one day before the end (90 days), the *trade* comes into effect, consisting of two transfers (*both*) between the parties. Otherwise, the contract becomes empty (*zero*) after 90 days.

The combinators for contracts are thus:

$$\begin{aligned} \text{zero} &: \text{Contr} \\ \text{transfer} &: \text{Party} \times \text{Party} \times \text{Currency} \rightarrow \text{Contr} \\ \text{scale} &: \text{Expr}_{\mathbb{R}} \times \text{Contr} \rightarrow \text{Contr} \\ \text{translate} &: \mathbb{N} \times \text{Contr} \rightarrow \text{Contr} \\ \text{checkWithin} &: \text{Expr}_{\mathbb{B}} \times \mathbb{N} \times \text{Contr} \times \text{Contr} \rightarrow \text{Contr} \\ \text{both} &: \text{Contr} \times \text{Contr} \rightarrow \text{Contr} \end{aligned}$$

The *translate* combinator simply translates a contract a number of days into the future. In the expression language, we also define a special expression *acc* which *accumulates* a value over a given number of days from today.

$$\text{acc} : (\text{Expr}_{\alpha} \rightarrow \text{Expr}_{\alpha}) \rightarrow \mathbb{N} \rightarrow \text{Expr}_{\alpha} \rightarrow \text{Expr}_{\alpha}$$

The accumulator can be used to compute averages (for so-called Asian options), or more generally to carry forward a state while computing values.

2.1 Denotational Semantics

The semantics of a contract is given by its cash-flow, which is a partial mapping from time to transfers between two parties:

$$\begin{aligned} \text{Trans} &= \text{Party} \times \text{Party} \times \text{Currency} \rightarrow \mathbb{R} \\ \text{Flow} &= \mathbb{N} \rightharpoonup \text{Trans} \end{aligned}$$

The cash-flow is a partial mapping since it may not be determined due to insufficient knowledge about observables and external decisions, provided by an environment $\rho \in \text{Env}$:

$$\begin{aligned} \text{Env} &= \mathbb{Z} \rightarrow X \rightarrow \mathbb{R} \cup \mathbb{B} \\ \mathcal{C}[\cdot] : \text{Contr} \times \text{Env} &\rightarrow \text{Flow} \end{aligned}$$

Note that the environment is a partial mapping from \mathbb{Z} , i.e. it may provide information about the past. This denotational semantics is the foundation for the formalisation of symbolic contract analyses, contract management and transformations.

An important property of the semantics of contracts is monotonicity, i.e.

$$\mathcal{C}[c]_{\rho_1} \subseteq \mathcal{C}[c]_{\rho_2} \text{ if } \rho_1 \subseteq \rho_2$$

where \subseteq denotes the subset inclusion of the graph of two partial functions.

2.2 Contract Analysis

When dealing with contracts we are interested in a number of semantic properties of contracts, e.g. causality (Does the cash-flow at each time t depend only on observables at time $\leq t$?), horizon (From which time onwards is the cash-flow always zero?) and dependencies (Which observables does the cash-flow depend on?). Such properties can be characterised precisely using the denotational semantics. For example a contract c is causal iff for all $t \in \mathbb{N}$ and $\rho_1, \rho_2 \in \text{Env}$ such that $s \leq t$ implies $\rho_1(s) = \rho_2(s)$ for all $s \in \mathbb{Z}$, we have that $\mathcal{C}[c]_{\rho_1}(t) = \mathcal{C}[c]_{\rho_2}(t)$. That is, the cash-flows at any time t do not depend on observables and decisions after t .

It is in general undecidable whether a contract is causal, but we can provide conservative approximations. For instance we have an inductively defined predicate *CAUSAL* such that if *CAUSAL*(c), then c is indeed causal. This is not unlike type checking, which provides a conservative approximation of type safety.

3 Management and Transformation

Apart from a variety of analyses, our framework provides functionality to transform contracts in meaningful ways. The most basic form of such transformations are provided by algebraic laws. These laws of the form $c_1 \equiv c_2$ state when it is safe to replace a contract c_1 by an equivalent contract c_2 . Using our denotational semantics, these algebraic laws can be proved in a straightforward manner: we have $c_1 \equiv c_2$ iff $\mathcal{C}[c_1]_{\rho} = \mathcal{C}[c_2]_{\rho}$ for all $\rho \in \text{Env}$.

More interesting are transformations that are based on knowledge about observables and external decisions. That is, we transform a contract c based on an environment $\rho \in \text{Env}$

that encodes the knowledge that we already have. We consider two examples, specialisation and reduction.

3.1 Specialisation

A specialisation function f performs a partial evaluation of a contract c under a given environment ρ . The resulting contract $f(c, \rho)$ is equivalent to c under the environment ρ . More generally, we have that $\mathcal{C} \llbracket f(c, \rho) \rrbracket_{\rho'} = \mathcal{C} \llbracket c \rrbracket_{\rho}$ for any environment $\rho' \subseteq \rho$, including the empty environment.

3.2 Reduction Semantics

The contract language is also equipped with a reduction semantics [1], which advances a contract by one time unit. We write $c \xrightarrow{\tau}_{\rho} c'$, to denote that c is advanced to c' in the environment ρ , where $\tau \in \text{Trans}$ indicates the transfers that are necessary (and sufficient) in order to advance c to c' . The reduction semantics can be implemented as a recursive function of type

$$f_{\Rightarrow} : \text{Contr} \times \text{Env} \rightarrow \text{Contr} \times \text{Trans}$$

The function f_{\Rightarrow} takes a contract c and an environment ρ , and returns the residual contract c' and the transfers τ such that $c \xrightarrow{\tau}_{\rho} c'$. The argument ρ typically contains the knowledge that we have about observables and decisions up to the present time, i.e. for time points ≤ 0 .

The reduction semantics is sound and complete w.r.t. the denotational semantics:

Theorem 1. *If $c \xrightarrow{\tau}_{\rho} c'$, then $\mathcal{C} \llbracket c \rrbracket_{\rho}(0) = \tau$ and $\mathcal{C} \llbracket c \rrbracket_{\rho}(i+1) = \mathcal{C} \llbracket c' \rrbracket_{\rho \uparrow}(i)$ for all $i \in \mathbb{N}$, where $\rho \uparrow(i) = \rho(i+1)$. If $\mathcal{C} \llbracket c \rrbracket_{\rho}(0) = \tau$ then there is some c' with $c \xrightarrow{\tau}_{\rho} c'$.*

4 Related and Future Work

Based on the seminal work by Peyton-Jones, Eber, and Seward [7], and even earlier work on contract languages [2], in the last decade, domain specific languages for contract specifications have been widely adopted by the financial industry [4, 5, 8], allowing for more agility,

shorter time-to-market for new products, and increased assurance of software quality.

For future work we plan to implement and certify more extensive analyses and transformations, e.g. scenario generation and “zooming” (changing the granularity of time). Moreover, an important goal is to generate from a contract efficient code to calculate its payoff [6]. The Haskell implementation is translated by hand into Coq definitions, which are the basis for the certification. This approach is beneficial for rapid prototyping, but our goal is to turn this process around and automatically extract Haskell code from the Coq definitions.

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