Quantified Class Constraints

Citation for published version:

Digital Object Identifier (DOI):
10.1145/3122955.3122967

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
ICFP Workshops 2017 - 10th ACM SIGPLAN International Haskell Symposium (Haskell 2017).

General rights
Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.
Quantified Class Constraints

Gert-Jan Bottu
KU Leuven
Belgium
gertjan.bottu@student.kuleuven.be

Georgios Karachalias
KU Leuven
Belgium
georgios.karachalias@cs.kuleuven.be

Tom Schrijvers
KU Leuven
Belgium
tom.schrijvers@cs.kuleuven.be

Bruno C. d. S. Oliveira
University of Hong Kong
China
bruno@cs.hku.hk

Philip Wadler
University of Edinburgh
UK
wadler@inf.ed.ac.uk

Abstract
Quantified class constraints have been proposed many years ago to raise the expressive power of type classes from Horn clauses to the universal fragment of Hereditary Harrop logic. Yet, while it has been much asked for over the years, the feature was never implemented or studied in depth. Instead, several workarounds have been proposed, all of which are ultimately stopgap measures.

This paper revisits the idea of quantified class constraints and elaborates it into a practical language design. We show the merit of quantified class constraints in terms of more expressive modeling and in terms of terminating type class resolution. In addition, we provide a declarative specification of the type system as well as a type inference algorithm that elaborates into System F. Moreover, we discuss termination conditions of our system and also provide a prototype implementation.

CCS Concepts
• Theory of computation → Type structures;
• Software and its engineering → Functional languages;

Keywords
Haskell, type classes, type inference

ACM Reference Format:
https://doi.org/10.1145/3122955.3122967

1 Introduction
Since Wadler and Blott [38] originally proposed type classes as a means to make adhoc polymorphism less adhoc, the feature has become one of Haskell’s cornerstone features. Over the years type classes have been the subject of many language extensions that increase their expressive power and enable new applications. Examples of such extensions include: multi-parameter type classes [19]; functional dependencies [18]; or associated types [3].

Several of these implemented extensions were inspired by the analogy between type classes and predicates in Horn clauses. Yet, Horn clauses have their limitations. As a small side-product of their work on derivable type classes, Hinze and Peyton Jones [12] have proposed to raise the expressive power of type classes to essentially the universal fragment of Hereditary Harrop logic [9] with what they call quantified class constraints. Their motivation was to deal with higher-kindied types which seemed to require instance declarations that were impossible to express in the type-class system of Haskell at that time.

Unfortunately, Hinze and Peyton Jones never did elaborate on quantified class constraints. Later, Lämmel and Peyton Jones [21] found a workaround for the particular problem of the derivable type classes work that did not involve quantified class constraints. Nevertheless the idea of quantified class constraints has whet the appetite of many researchers and developers. GHC ticket #2893, requesting for quantified class constraints, was opened in 2008 and is still open today. Commenting on this ticket in 2009, Peyton Jones states that “their lack is clearly a wart, and one that may become more pressing”, yet clarifies in 2014 that “(t)he trouble is that I don’t know how to do type inference in the presence of polymorphic constraints.” In 2010, 10 years after the original idea, Hinze [10] rues that the feature has not been implemented yet. As recently as 2016, Chauhan et al. [4] regret that “Haskell does not allow the use of universally quantified constraints” and now in 2017 Spivey [34] has to use pseudo-Haskell when modeling with quantified class constraints. While various workarounds have been proposed and are used in practice [20, 31, 36], none has stopped the clamor for proper quantified class constraints.

This paper finally elaborates the original idea of quantified class constraints into a fully fledged language design. Specifically, the contributions of this paper are:

• We provide an overview of the two main advantages of quantified class constraints (Section 2):
  1. they provide a natural way to express more of a type class’s specification, and
  2. they enable terminating type class resolution for a larger class of applications.

• We elaborate the type system sketch of Hinze and Peyton Jones [12] for quantified type class constraints into a full-fledged formalization (Section 3). Our formalization borrows the idea of focusing from CoqHs [32], a calculus for Scala-style implicits [26, 27], and adapts it to the Haskell setting. We account for two notable differences: a global set of non-overlapping instances and support for superclasses.

• We present a type inference algorithm that conservatively extends that of Haskell 98 (Section 4) and comes with a dictionary-passing elaboration into System F (Section 5).
What is not formally expressed in the above type class declaration,

h

A second-order functor

The idea of this code is to

2 Motivation

This section illustrates the expressive power afforded by quantified

class constraint

to functors. This can be concisely expressed with the quantified

polymorphic lists and trees, as the fixpoint

2.1 Precise and Succinct Specifications

Monad Transformers Consider the MTL type class for monad

t = (\forall f. \text{Functor}\ f \Rightarrow \text{Functor}\ (h\ f)) \Rightarrow \text{HFunctor}\ h\ \text{where}

hfmap :: (\text{Functor}\ f, \text{Functor}\ g)\ \Rightarrow\ (\forall x. f\ x \rightarrow g\ x)\ \rightarrow\ (\forall x. h\ f\ x \rightarrow h\ g\ x)

data HPerf\ f\ a = HZero\ a | HSucc\ f\ (a, a)

Johann and Ghani’s notion of second-order functor differs slightly

from Hinze’s.3 Ideally, their notion would be captured by the following
class declaration:

class HFunctor\ h\ where

hfmap :: (\text{Functor}\ f, \text{Functor}\ g)\ \Rightarrow\ (\forall x. f\ x \rightarrow g\ x)\ \rightarrow\ (\forall x. h\ f\ x \rightarrow h\ g\ x)

In essence, they inline the fmap method provided by the quantified

class constraint in the HFunctor class. This is unfortunate because it duplicates the Functor class’s functionality.

2.2 Terminating Corecursive Resolution

Johann and Ghani use essentially the same data-generic representa-
tion, the fixpoint of second-order functors, to represent so-called nested datatypes [2]. For instance, Hinze [16] represents perfect binary trees with the nested datatype

data Perfect\ a = Zero\ a | Succ\ (Perfect\ (a, a))

This can be expressed with the generic representation as Mu HPerf,

the fixpoint of the second-order functor HPerf, defined as

data HPerf\ f\ a = HZero\ a | HSucc\ f\ (a, a)

Johann and Ghani’s notion of second-order functor differs slightly

from Hinze’s.3 Ideally, their notion would be captured by the following

class declaration:

class HFunctor\ h\ where

hfmap :: (\text{Functor}\ f, \text{Functor}\ g)\ \Rightarrow\ (\forall x. f\ x \rightarrow g\ x)\ \rightarrow\ (\forall x. h\ f\ x \rightarrow h\ g\ x)

In essence, they inline the fmap method provided by the quantified

class constraint in the HFunctor class. This is unfortunate because it duplicates the Functor class’s functionality.

2.2 Terminating Corecursive Resolution

Quantified class constraints were first proposed by Hinze and Pey-
ton Jones [12] as a solution to a problem of diverging type class

resolution. Consider their generalized rose tree datatype

data GRose\ f\ a = GBranch\ a\ (f\ (\text{GRose}\ f\ a))

and its Show instance

instance (Show\ a, Show\ (f\ (\text{GRose}\ f\ a)))\ \Rightarrow\ Show\ (\text{GRose}\ f\ a)

where\ show\ (\text{GBranch}\ x\ xs) = \text{unwords}\ [\text{show}\ x, \text{"-"}, \text{show}\ xs]

Notice the two constraints in the instance context which are due to the two show invocations in the method definition. Standard recursive type class resolution would diverge when faced with the constraint (Show\ (\text{GRose}\ []\ Bool)). Indeed, it would recursively resolve the instance context: Show Bool is easily dismissed, but Show\ (\text{GRose}\ []\ a) requires resolving Show (GRose [] Bool) again. Clearly this process loops.

To solve this problem, Hinze and Peyton Jones proposed to write the GRose instance with a quantified type class constraint as:

instance (Show\ a, \forall x. Show\ x \Rightarrow Show\ (f\ x))\ \Rightarrow\ Show\ (\text{GRose}\ f\ a)

where\ show\ (\text{GBranch}\ x\ xs) = \text{unwords}\ [\text{show}\ x, \text{"-"}, \text{show}\ xs]

3 It is more in line with the category theoretical notion of endofunctors over the category of endofunctors.
This would avoid the diverging loop in the type system extension they sketch, because the two recursive resolvents, Show Bool and ∀x.Show x ⇒ Show [x] are readily discharged with the available Bool and [a] instances.

When faced with the same looping issue in their Scrap Your Boilerplate work, Lønning and Peyton Jones [22] implemented a different solution: cycle-aware constraint resolution. This approach detects that a recursive resolvent is identical to one of its ancestors and then ties the (co-)recursive knot at the level of the underlying type class dictionaries.

Unfortunately, cycle-aware resolution is not a panacea. It only deals with a particular class of diverging resolutions, those that cycle. The fixpoint of the second-order functor HPerf presented above is beyond its capabilities.

We allow a more general form of constraints where, in analogy to the previous examples, Show Bool and ∀x.Show x ⇒ Show [x] are readily discharged with the available Bool and [a] instances.

In contrast, with quantified type class constraints we can formulate the instances in a way that resolution does terminate.

In summary, quantified type class constraints enable 1) expressing more of a type class’s specification in a natural and succinct manner, and 2) terminating type class resolution for a larger group of applications.

In the remainder of this paper we provide a declarative type system for a Haskell-like calculus with quantified class constraints (Section 3). Type inference is shown in Section 4 and Section 5 provides an elaboration into System F. Section 6 presents the conditions we require to ensure termination in the presence of quantified class constraints. Finally, Section 7 discusses related work and Section 8 concludes.

3 Declarative Type System

This section provides the declarative type system specification for our core Haskell calculus with quantified class constraints.

Figure 1. Source Syntax

3.1 Syntax

Figure 1 presents the, mostly standard, syntax of our source language. A program pgm consists of class declarations cls, instance declarations inst and a top-level expression e. For simplicity, each class has a single parameter and a single method.

Terms e comprise a λ-calculus extended with let-bindings. By convention, we use f to denote a method name and x, y, z to denote any kind of term variable name.

Types also appear in Figure 1. Like all extensions of the Damas-Milner system [5] with qualified types [14], we discriminate between monotypes τ, qualified types ρ and type schemes σ. Note that, to avoid clutter, our formalization does not feature higher-kindred types, but our prototype implementation does.

Our calculus differs from Haskell’98 in that it conservatively generalizes the language of constraints. In Haskell’98 the constraints that can appear in type signatures and in class and instance contexts are basic class constraints Q of the form TC τ. As a consequence, the constraint schemes or axioms that are derived from instances (and for superclasses) are Horn clauses of the form:

∀a.Q₁ ∧ . . . ∧ Qₙ ⇒ Q₀

These axioms are similar to rank-1 polymorphic types in the sense that the quantifiers (and the implication) only occur on the outside. We allow a more general form of constraints C where, in analogy with higher-rank types, quantifiers and implications occur in nested positions. This more expressive form of constraints can occur in signatures and class-instance contexts. Consequently, the syntactic sort C of constraints and axioms is one and the same.

Note that constraint schemes of the form ∀a.(Q₁ ∧ . . . ∧ Qₙ) ⇒ Q₀, used in earlier formalizations of type classes (e.g., [25]), are not valid syntax for our constraints C because we do not provide a notation for conjunction. Yet, we can easily see the scheme notation as syntactic sugar for a curried representation:

∀a.(Q₁ · · · ∧ Qₙ) ⇒ Q₀ ⇔ ∀a.Q₁ ⇒ ( . . . (Qₙ ⇒ Q₀) . . . )
We denote a list of $C$-constraints as $A$, short for axiom set as we use them to represent, among others, axioms given through type class instances.

Finally, Figure 1 presents typing environments $\Gamma$, which are entirely standard, and the program theory $P$. The latter is a triple of three axiom sets: the superclass axioms $A_S$, the instance axioms $A_I$, and local axioms $A_L$. We use the notation $P, C$ to denote that we extend the local component of the type, and similar notation for the other components. In earlier type class formalizations these separate kinds of axioms are typically conflated into a single axiom set. However, in this paper it is convenient to distinguish them for accurately stating the different restrictions imposed on them. Moreover, it is instructive for contrasting with regular Haskell. In Haskell, the local constraints are basic type class constraints $\varnothing$ only, while the instance and superclass axioms have the more expressive Horn clause form. In contrast, in our setting all three components support the same (and more general) form of Harrop formulae.

### 3.2 The Type System

Figure 2 presents the main judgments of our declarative type system for the language of Figure 1, namely term typing and typing of class and instance declarations.

#### Type & Constraint Well-Scopedness

The judgments for well-scopedness of types, constraints and axiom sets are denoted $\Gamma_{h_{\sigma}}, \Gamma_{h_{\sigma}} C$ and $\Gamma_{h_{\sigma}} A$, respectively. Their definitions are straightforward and can be found in Appendix A.

#### Term Typing

Term typing takes the form $P, \Gamma_{h_{\sigma}} e : \sigma$ and can be read as "under program theory $P$ and typing environment $\Gamma$, expression $e$ has type $\sigma."$. The rules are almost literally those of Chakravarty et al. [3]. There is only one difference, which is a simplification for the sake of convenience: following Vytiniotis et al. [37] we have opted for recursive let-bindings that are not generalized. Nevertheless, we generalize the type of top-level bindings (see Appendix A).

Apart from that, there are no noticeable differences with conventional Haskell in the typing rules. All the interesting differences are concentrated in the definition of the constraint entailment judgment $P, \Gamma \vdash C$, which is used in the constraint elimination Rule (⇒E). The definition of this auxiliary judgment is discussed in detail in Section 3.3.

#### Class Declaration Typing

Typing for class declarations takes the form $\Gamma_{h_{\tau}} cls : A_S$ and is given by Rule CLASS, presented in Figure 2.

In addition to checking the well-formedness of the method type, we ensure that the class context $(C_1, \ldots, C_n)$ is also well-formed, extending the environment with the local variable $a$. In turn, this implies that $fv(C_i) \not\subseteq \{a\}$, in line with the Haskell standard.

As usual, typing a class declaration extends the typing environment with the method typing, and the program’s theory with the superclass axioms. For instance, the extended monad transformer class yields the superclass axiom:

$$\forall a. \text{Trans } t \Rightarrow (\forall m. \text{Monad } m \Rightarrow \text{Monad } (t m))$$

#### Class Instance Typing

Instance typing takes the form $P, \Gamma_{h_{\tau}} inst : A_I$ and is given by Rule INSTANCE, also presented in Figure 2.

We check the well-formedness of the instance context $A$ under the extended typing environment, and that each superclass constraint $C_i$ is entailed by the instance context.

Finally, we check that the method implementation $e$ has the type indicated by the class declaration, appropriately instantiated for the instance in question.

#### Program Typing

The judgment for program typing ties everything together and takes the form $P, \Gamma_{h_{\tau}} pgm : \sigma$. Its definition is straightforward and can be found in Appendix A.

### 3.3 Constraint Entailment

Following the approach of Schrijvers et al. [32] for their COCHIS calculus, we present constraint entailment in two steps. First, we provide an easy-to-understand and expressive, yet also highly ambiguous, specification. Then we present a syntax-directed, semi-algorithmic variant that takes the ambiguity away, but has a more complicated formulation inspired by the focusing technique used in proof search [1, 23, 24].
Declarative Specification

Constraint entailment takes the form $P;\Gamma \models C$, and its high-level declarative specification is given by the following rules:

\[
\begin{align*}
C & \in P, \Gamma \models C & P, \Gamma, a \models C & P, \Gamma \models \forall a.C & P, \Gamma \models \forall \mu a.C & (\forall \mu) C \\
\end{align*}
\]

If we interpret constraints $C$ as logical formulas, the above rules are nothing more than the rules of the universal fragment of Hereditary Harrop logic [9]. Rule (SpecC) is the standard axiom rule. Rules ($\Rightarrow IC$) and ($\Rightarrow EC$) correspond to implication introduction and elimination, respectively. Similarly, Rules (VIC) and (VEC) correspond to introduction and elimination of universal quantification, respectively. These are also essentially the rules Hindze and Peyton Jones [12] propose.

While compact and elegant, there is a serious downside to these rules: They are highly ambiguous and give rise to many trivially different proofs for the same constraint. For instance, assuming $\Gamma = \bullet, a$ and $P = \bullet, \bullet, \bullet, Eq a$, here are only two of the infinitely many proofs of $P;\Gamma \models Eq a$:

\[
\begin{align*}
Eq a \in P & \Rightarrow \Gamma \models Eq a & (\text{SpecC}) \\
Eq a \in P & \Rightarrow P', \Gamma \models Eq a & (\Rightarrow IC) \\
\end{align*}
\]

where $P' = P, Eq a$. Observe that the latter proof makes an unnecessary appeal to implication introduction.

Type-Directed Specification

To avoid the trivial forms of ambiguity like in the example, we adopt a solution from proof search known as focusing [1]. This solution was already adopted by the CoqHs calculus, for the same reason. The key idea of focusing is to provide a syntax-directed definition of constraint entailment where only one inference rule applies at any given time.

Figure 3 presents our definition of constraint entailment with focusing. The main judgment $P;\Gamma \models C$ is defined in terms of two auxiliary judgments, $P;\Gamma \models [C]$ and $\Gamma;[C] \models Q \rightsquigarrow A$, each of which is defined by structural induction on the constraint enclosed in square brackets.

The main entailment judgment is equivalent to the first auxiliary judgment $P;\Gamma \models [C]$. This auxiliary judgment focuses on the constraint $C$ whose entailment is checked — we call this constraint the "goal". There are three rules, for the three possible syntactic forms of $C$. Rules ($\Rightarrow R$) and ($\Rightarrow HR$) decompose the goal by applying implication and quantifier introductions respectively. Once the goal is stripped down to a simple class constraint $Q$, Rule ($\Rightarrow F$) selects an axiom $C$ from the theory $P$ to discharge it. The selected axiom must match the goal, a notion that is captured by the second auxiliary judgment. Matching gives rise to a sequence $A$ of new (and hopefully simpler) goals whose entailment is checked recursively.

3.4 Remaining Nondeterminism

While focusing makes the definition of constraint entailment type-directed, there are still two sources of nondeterminism. As a consequence, the specification is still ambiguous and not an algorithm.

Overlapping Axioms

The first source of non-determinism is that in Rule ($\Rightarrow F$) there may be multiple matching axioms that make the entailment go through. For applications of logic where proofs are irrelevant this is not a problem, but in Haskell where the proofs have computational content (namely the method implementations) this is a cause for concern. Haskell’98 also faces this problem. Consider two instances for the same type:

\[
\begin{align*}
\text{class} & \text{ Default a where } \{ \text{default} :: a \} \\
\text{instance} & \text{ Default Bool where } (\text{default} = \text{True}) \\
\text{instance} & \text{ Default Bool where } (\text{default} = \text{False})
\end{align*}
\]

\[\text{Without loss of expressive power. See for example [50].}\]
The two instances give rise to two different proofs for `Default Bool`, with distinct computational content (`True vs. False`). We steer away from this problem in the same way as Haskell'98, by requiring that instance declarations do not overlap. This does not rule out the possibility of distinct proofs for the same goal, but at least distinct proofs have the same computational content. Consider a class hierarchy where `C` is the superclass of both `D` and `E`.

\[
\begin{align*}
\text{class } & \text{ } C a \text{ where } \{ \ldots \} \\
\text{class } & \text{ } D a \text{ where } \{ \ldots \} \\
\text{class } & \text{ } E a \text{ where } \{ \ldots \} \\
\end{align*}
\]

This gives rise to the superclass axioms `∀a. D a ⇒ C a` and `∀a. E a ⇒ C a`. Given additionally two local constraints `D τ` and `E τ`, we have two ways to establish `C τ`. The proofs are distinct, yet ultimately the computational content is the same. This is easy to see as only instances supply the computational content and there can be at most one instance for any given type `τ`.

In summary, non-overlap of instances is sufficient to ensure coherence.

**Guessing Polymorphic Instantiation** A second source of ambiguity is that Rule `(∀L)` requires guessing an appropriate type `τ` for substituting the type variable `b`. Guessing is problematic because there are an infinite number of types to choose from and more than one of those choices may cause the entailment work out. Choosing an appropriate type is a problem for the type inference algorithm in the next section. Different choices leading to different proofs is a more fundamental problem that also manifests itself in Haskell'98.

Consider the following instances.

\[
\begin{align*}
\text{instance } & \text{ } C \text{ Char where } \{ \ldots \} \\
\text{instance } & \text{ } C \text{ Bool where } \{ \ldots \} \\
\text{instance } & \text{ } C a ⇒ D \text{ Int where } \{ \ldots \} \\
\end{align*}
\]

The third instance gives rise to the axiom `∀a. C a ⇒ D Int`. When resolving `D Int` with this axiom we can choose `a` to be either `Char` or `Bool` and thus select a different `C` instance.

Haskell'98 avoids this problem by requiring that all quantified type variables, like `a` in the example, appear in the head of the axiom. Because our axioms have a more general, recursively nested form, we generalize this requirement in a recursively nested fashion. The predicate `unamb(C)` in Figure 4 formalizes the requirement in terms of the auxiliary judgment `\( \overline{a} \triangleleft \triangleright \overline{Q} \)`, where `\( \overline{a} \)` are type variables that need to be determined by the head of `C`. Rule `(Q)` constitutes the base case where `\( \overline{Q} \)` is the head and contains the determinable type variables `\( \overline{a} \)`.

**4 Type Inference**

We provide a type inference algorithm with elaboration into System F [7]. To simplify the presentation, this section focuses solely on type inference. The parts of the rules highlighted in gray concern elaboration and are discussed in Section 5.

To make the connection to the relations of the declarative specification (Section 3.2) more clear, corresponding rules share the same name.

4.1 Preliminaries

Before diving into the details of the algorithm, we first introduce some additional notation and constructs.

**Variable-Annotated Constraints & Type Equalities** Since our goal is to perform type inference and elaboration to System F simultaneously, we annotate all constraints with their corresponding System F evidence term (dictionary variable `d`). We keep the notational burden minimal by reusing the same letters as in Figure 1, yet with a calligraphic font:

\[
\begin{align*}
\mathcal{P} & := \langle \mathcal{A}_S, \mathcal{A}_I, \mathcal{A}_L \rangle & \text{variable-annotated theory} \\
\mathcal{A} & := \bullet | \mathcal{A}, C & \text{variable-annotated axiom set} \\
C & := \mathcal{A} \triangleleft \mathcal{C} & \text{variable-annotated constraint} \\
\mathcal{Q} & := \mathcal{A} \triangleleft \mathcal{Q} & \text{variable-annotated class constraint} \\
E & := \bullet | E, τ_1 \sim τ_2 & \text{type equalities} \\
\end{align*}
\]

**Type & Evidence Substitutions** Furthermore, we introduce two kinds of substitutions: type substitutions `θ` and dictionary substitutions `η`:

\[
\begin{align*}
\theta & := \bullet | \theta \cdot [\tau / a] & \text{type substitution} \\
\eta & := \bullet | \eta \cdot [t / d] & \text{evidence substitution} \\
\end{align*}
\]

A type substitution `θ` maps type variables to monotypes, while an evidence substitution `η` maps dictionary variables `d` to System F terms `t` (see Section 5.1 for the formal syntax of System F terms).

4.2 Constraint Generation For Terms

Figure 5 presents constraint generation for terms. The relation takes the form `\( \Gamma \vdash_{\text{sym}} \tau \Rightarrow \mathcal{A}, E \)`. Given a typing environment `\( \Gamma \)` and a term `\( e \)` we infer (1) a monotype `\( τ \)` (2) a set of wanted constraints `\( \mathcal{A} \)`, and (3) a set of wanted equalities `\( E \)`.

---

**Figure 4. Unambiguity**
### Constraint Simplification

Rule $\text{TmVar}$ handles variables. We instantiate the polymorphic type $\forall \alpha C \Rightarrow \tau$ of a term variable $x$ with fresh unification variables $\vec{\eta}$, introducing $C$ as wanted constraints, instantiated likewise. Rule $\text{TmAbs}$ assigns a fresh unification variable to the abstracted term variable $x$, and adds it to the context for checking the body of the abstraction. Rule $\text{TmApp}$ handles applications ($e_1 e_2$). We collect wanted class and equality constraints from each subterm, we generate a fresh type variable $a$ for the result and report that the type of $e_1$ is a function type $(a_1 \sim a_2 \Rightarrow a)$. Rule $\text{TmLet}$ handles (possibly recursive) let bindings.

### 4.3 Constraint Solving

The type and equality constraints derived from terms are solved with the following two algorithms.

#### Solving Equality Constraints

We solve a set of equality constraints $E$ by means of unification. The function $\text{unify}(\vec{\alpha}, E) = \theta_1$ takes the set of equalities and a set of "untouchable" type variables, and returns either the most general unifier $\theta$ of the equalities or fails if none exists. The untouchable type variables $\vec{\alpha}$ originate from type signatures; all other type variables are unification variables. The unifier is of course only allowed to substitute unification variables.

The definition of this unification function is folklore, following Damas and Milner [5] and accounting for signatures; it can be found in Appendix A.

#### Solving Type Class Constraints

Figure 6 defines the judgment for solving type class constraints; it takes the form $\vec{\pi}, \mathcal{P} \vdash [\mathcal{A}] \Rightarrow \mathcal{A}_1; \vec{\eta}$. Given a set of unTouchable type variables $\vec{\alpha}$ and a theory $\mathcal{P}$, it (exhaustively) replaces a set of constraints $\mathcal{A}_1$ with a set of simpler, residual constraints $\mathcal{A}_2$, via the auxiliary judgment $\vec{\pi}, \mathcal{P} \vdash [\mathcal{C}] \Rightarrow \mathcal{A}_2; \vec{\eta}$, explained below.

This form differs from the specification in Figure 3: we allow constraints to be partially entailed, which in turn allows us to perform simplification [17] of top-level signatures. This is standard practice in Haskell when inferring types. For instance, when inferring the signature for

$$f \ x = [x]$$

Haskell simplifies the derived constraint $Eq \ [a]$ to $Eq \ a$, yielding the signature $\forall \alpha.Eq \ a \Rightarrow a \Rightarrow \text{Bool}$.

#### Simplification

Auxiliary judgment $\vec{\pi}, \mathcal{P} \vdash [\mathcal{C}] \Rightarrow \mathcal{A}; \vec{\eta}$ uses the theory $\mathcal{P}$ to simplify a single constraint $\mathcal{C}$ to a set of simpler constraints without instantiating any of the untouchable type variables $\vec{\alpha}$. Following the focusing approach, the judgment is defined by three rules, one for each of the syntactic forms of the goal $\mathcal{C}$.

Rules $(\Rightarrow R)$ and $(\Rightarrow V)$ recursively simplify the head of the goal. Observe that we add the bound variable $b$ to the untouched $\vec{\alpha}$ when going under a binder in Rule $(\Rightarrow V)$. Once the goal is stripped down to a simple class constraint $Q$, Rule $(\Rightarrow Q)$ selects an axiom $C$ whose head matches the goal, and uses it to replace the goal with a set of simpler constraints $\mathcal{A}$ (a process known as context reduction [16]). Goal matching is performed by judgment $\vec{\pi}, [\mathcal{C}] \vdash Q \Rightarrow \mathcal{A}; \theta; \vec{\eta}$, discussed below.

#### Matching

Auxiliary judgment $\vec{\pi}, [\mathcal{C}] \vdash Q \Rightarrow \mathcal{A}; \theta; \vec{\eta}$ focuses on the axiom $\mathcal{C}$ and checks whether it matches the simple goal $Q$. The main difference between this algorithmic relation and its declarative specification in Figure 3 lies in the type substitution $\theta$. Instead of guessing a type for instantiating a polymorphic axiom...
The reason is that our local axioms are not necessarily simple

class Instance Typing

Figure 7 defines declaration typing of class and instance declarations.

Given local axioms $D a$, $F a$ and $G a$, consider what happens when
we resolve the goal $C a$. The superfamilies $E a \Rightarrow C a$ and $G a \Rightarrow C a$
of respectively $D a$ and $F a$ both match this goal. If we pick the first
one, we get stuck when recursively resolving $E a$. However, if we
backtrack and consider the second one instead, we can recursively
resolve $G a$ against the given local constraint.

In summary, because we do not see a general way to avoid search,
our prototype implementation uses backtracking for choosing be-
tween the different axioms.

Implementation Our prototype implementation is available at
https://github.com/gkaracha/quantcs-impl. It incorporates high-

Search As Section 3.4 has remarked, there may be multiple matching
axioms, e.g., due to overlapping superclass axioms. The straight-

forward algorithmic approach to the involved nondeterminism is
search, possibly implemented by backtracking. The GHC Haskell
implementation can employ a heuristic to keep this search shallow.
It does so by using the superclass constraints very selectively: when-
ever a new local constraint is added to the theory, it pro-actively
derives all its superfamilies and adds them as additional local ax-

In our setting, we can also implement a (modified version) of
GHC’s heuristic, but this does not obviate the need for deep search.
The reason is that our local axioms are not necessarily simple
axioms, and matching against them may leave residual goals that
require further recursive resolution. When that recursive resolution
gets stuck, we have to backtrack over the choice of axiom. Consider
the following example.

\[\begin{align*}
\text{class } (E a \Rightarrow C a) & \Rightarrow D a \\
\text{class } (G a \Rightarrow C a) & \Rightarrow F a
\end{align*}\]
Without loss of generality, we simplify matters by allowing only as wanted constraints
This section discusses the elaboration aspect of the algorithm pre-
Type inference and elaboration for programs is straightforward
Our dictionary-passing translation of type classes.

standard. Like in the source language, we elide all mention of kinds.
and recursive let-bindings – is presented in Figure 9 and is entirely
The syntax of System F [7] – extended with data types

Quantified Class Constraints [8, 38]. This transition is reflected in the trans-
so-called dictionaries [8, 38]. This transition is reflected in the trans-
lation of types, performed by judgment \( h_1 \sigma \leadsto v \):

Rules TyVAR, TyArr and TyALL are straightforward. Rule TyQUAL elab-
(which performs elaboration of constraints):

Rule (CQ) elaborates a class constraint \((TC \tau)\) into a type construc-
tor application \((T_{TC} \tau)\), which corresponds to the type of diction-
aries that witness \((TC \tau)\). Rule (CV) is straightforward. Rule (C=) elab-
orates implication constraints of the form \((C_1 \Rightarrow C_2)\) into
System F arrow types \((v_1 \rightarrow v_2)\), that is, types of dictionary trans-
formers. As a concrete example, the constraint corresponding to the
Show instance for type \(HPeRF\) (Section 2.2):

\[ \forall f. Show a \Rightarrow (\forall x. Show x \Rightarrow Show (f x)) \Rightarrow Show (HPeRF f a) \]

elaborated into the type

\[ \forall f. A.\overline{T}_{Show} a \Rightarrow (\forall x. \overline{T}_{Show} x \Rightarrow \overline{T}_{Show} (f x)) \Rightarrow \overline{T}_{Show} (HPeRF f a) \]

5.3 Elaboration of Terms

Term elaboration is straightforward. Rule TmVAR handles term vari-
ables. The instantiation of the type scheme \(\forall a. C \Rightarrow \tau\) to \([\overline{b}]\overline{\tau}\) be-
comes explicit in the System F representation, by the application of
x to type variables \(\overline{b}\) as well as the fresh dictionary variables \(\overline{d}\),
corresponding one-to-one to the implicit constraints \(\overline{C}\). Rule TmAbs en-
larates \(\lambda\)-abstractions. Since in System F all bindings are explicit-
ly typed, in the elaborated term we annotate the binding of x with its
ypical a. Similarly, Rule TmLet elaborates let bindings, again explicit-
ly annotating x with its type \(v_1\) in the elaborated term.

Rule TmAPP is straightforward.

5.4 Dictionary Construction

The entailment algorithm of Figure 6 constructs explicit witness
proofs (in the form of dictionary substitutions) while entail-
ing a constraint.

\[ \eta \] illustrates how to generate a proof for \((d_2 : C_2)\), from the local
assumption \((d_1 : C_1)\) and local residual constraints \((\overline{d} : C)\).
Accordingly, we generate the evidence substitution via constraint matching, which we discuss next.

**Matching** Similarly, the evidence substitution \( \eta \) in the matching relation shows how to construct a witness for the wanted constraint \( Q \) from the simpler constraints \( A \) and program theory \( P \).

Rule \((\Rightarrow L)\) generates two fresh dictionary variables, \( d_1 \) for the residual constraint \( \theta(C_1) \), and \( d_2 \) for the local assumption \( C_2 \). Finally, dictionary \( d_2 \) is replaced by the application of the dictionary transformer \( T \) to the residual dictionary \( d_1 \). Rule \((\forall L)\) behaves similarly.

The instantiation of the axiom \( d \) becomes explicit, by applying it to the chosen type \( \theta(b) \). Finally, Rule \((Q L)\) is straightforward: since the wanted and the given constraints are identical (given that they unify), the wanted dictionary \( d \) is replaced by the given \( d' \).

### 5.5 Declaration Elaboration

Figure 7 presents the elaboration of both class and instance declarations into System F.

**Elaboration of Class Declarations** A declaration for a class \( TC \) is encoded in System F as a dictionary type \( T_C \), with a single data constructor \( K_T \) and \( n + 1 \) arguments: \( n \) arguments for the superclass dictionaries (of type \( \overrightarrow{v} \)) and one more for the method implementation (of type \( v \)). For example, the \( Trans \) declaration of Section 2.1 gives rise to the following dictionary type:

\[
\text{data } \text{Trans } t = K_{\text{Trans}} \quad (\forall m. \text{Trans } t \to \text{Trans } t) m \quad (\forall a. \text{Trans } t \to a \to \text{Trans } t a)
\]

Accordingly, we generate \( n + 1 \) projection functions that extract each of the arguments \( d_i \) extracts the \( i \)-th superclass dictionary and \( f \) the method implementation. We use \( \text{proj}_{K_{TC}}(d) \) to denote pattern matching against \( d \) and extracting the \( i \)-th argument:

\[
\text{proj}_{K_{TC}}(d) = \text{case } d \text{ of } K_{TC} x^k \to x_i, \quad x^k \text{ fresh}
\]

where \( k \) denotes the arity of data constructor \( K_{TC} \). E.g., the superclass projection function for class \( Trans \) takes the form:

\[
d_{sc} : \forall t. \text{Trans } t \to (\forall m. \text{Trans } t m \to \text{Trans } t (m a \to (m a) a))
\]

**Elaboration of Class Instances** A class instance is elaborated into a System F dictionary transformer \( d_I \):

\[
\text{let } d_I = (\forall \overrightarrow{v}. T_{TC} \to T_{TC} t) = \Delta \overrightarrow{x}. \lambda (d : \overrightarrow{v}). K_{TC} \tau \eta(d') t
\]

Given dictionaries \( d - \) corresponding to the given context constraints – we need to provide all arguments of the data constructor \( K_{TC} \): (a) the instantiation of the class type parameter, (b) the superclass dictionaries, and (c) the method implementation. The first argument is trivial. We obtain the superclass dictionaries by applying the evidence substitution \( \eta \) on the dictionary variables \( d'- \) that abstract over the required superclass constraints. The method implementation \( t \) is elaborated via premise

\[
\overrightarrow{v}, \overrightarrow{P}; \Gamma \vdash a : \tau \to a\sigma \Rightarrow t
\]

which elaborates type subsumption in a similar manner.

### 6 Termination of Resolution

Termination of resolution is the cornerstone of the overall termination of type inference. This section discusses how to enforce termination by means of syntactic conditions on the axioms. These conditions are adapted from those of Cochis [32] and generalize the earlier conditions for Haskell by Sulzmann et al. [35].

**Overall Strategy** We show termination by characterising the resolution process as a (resolution) tree with goals in the nodes and axioms on the (multi-)edges. The initial goal sits at the root of the tree. A multi-edge from a parent node to its children presents an axiom that matches the parent node’s goal and its children are the residual goals. Resolution terminates iff the tree is finite. Hence, if it does not terminate, there is an infinite path from the root in the tree, that denotes an infinite sequence of axiom applications.

To show that there cannot be such an infinite path, we use a norm \( \| \| \) that maps the head \(^2\) of every goal \( C \) to a natural number, its size. The size of a class constraint \( TC \) is the size of its type parameter \( r \), which is given by the following equations:

\[
\begin{align*}
\|a\| &= 1 \\
\|k \rightarrow \tau\| &= \|k\| + \|\tau\|
\end{align*}
\]

If we can show that this size strictly decreases from any parent goal to its children, then we know that, because the order on the natural numbers is well-founded, on any path from the root there is eventually a goal that has no children.

**Termination Condition** It is trivial to show that the size strictly decreases, if we require that every axiom makes it so. This requirement is formalised as the termination condition of axioms \( term(C) \):

\[
\begin{align*}
\text{term}(Q) & \Rightarrow \text{term}((\forall a. C) (\forall a. C)) \\
\|Q_1 \rightarrow \tau_2\| & = \|Q_1\| + \|\tau_2\|
\end{align*}
\]

Rule \((\Rightarrow T)\) for \( C_1 \Rightarrow C_2 \) enforces the main condition, that the size of the residual constraint’s head \( Q_1 \) is strictly smaller than the head \( Q_2 \) of \( C_2 \). In addition, the rule ensures that this property is stable under type substitution. Consider for instance the axiom \( \forall a. C (a \rightarrow a) \Rightarrow C (a \rightarrow \text{Int} \rightarrow \text{Int}) \). The head’s size 5 is strictly greater than the context constraint’s size 3. Yet, if we instantiate \( a \) to \( \text{Int} \rightarrow \text{Int} \rightarrow \text{Int} \), then the head’s size becomes 10 while the context constraint’s size becomes 11. Declaratively, we can formulate stability as:

\[
\forall \theta, \text{dom}(\theta) \subseteq \text{fv}(C_1) \cup \text{fv}(C_2) \Rightarrow \|\theta(Q_1)\| < \|\theta(Q_2)\|
\]

The rule uses instead an equivalent algorithmic formulation which states that the number of occurrences of any free type variable \( a \) may not be larger in \( Q_1 \) than in \( Q_2 \). Here the number of occurrences of a type variable \( a \) in a class constraint \( TC \) (denoted as

\(^2\) The head of a constraint is defined as: \( \text{head}(Q) = Q; \text{head}(\forall a. C) = \text{head}(C); \) and \( \text{head}(C_1 \Rightarrow C_2) = \text{head}(C_2). \)
Quantified Class Constraints

Abstract

We have preserved the variant that the goal size decreases after a single
instance contexts – actually the contexts are just parameters. For instance, we can model the Trans class as:

\texttt{class Trans \((T : \text{Type} \rightarrow \text{Type}) \rightarrow \text{Type} \rightarrow \text{Type})
\}

\(\{\text{forall M, } \{\text{Monad } \rightarrow \text{Monad } (T \ M)\} \rightarrow
\{\text{lift : forall A M, } \{\text{Monad } \rightarrow \text{M A } \rightarrow (T \ M) \ A\} \)\).

The downside of Coq’s flexibility is that resolution can be ambiguous and non-terminating. The accepted workaround is for the programmer to perform resolution manually when necessary. This is acceptable in the context of Coq’s interactive approach to proving, but would mean a great departure from Haskell’s non-interactive type inference.

Trifonov’s Workaround and Monatron Trifonov [36] gives an encoding of quantified class constraints in terms of regular class constraints. The encoding introduces a new type class that encapsulates the quantified constraint, e.g. \texttt{Monad tt for \forall m. Monad m ⇒ Monad (t m)}, and that provides the implied methods under a new name. This expresses the \texttt{Trans} problem as follows:

\texttt{class Monad_t t where}
\begin{align*}
\text{treturn} & : \text{Monad m ⇒ m a } \rightarrow \text{m a} \\
\text{tbind} & : \text{Monad m ⇒ m a } \rightarrow \text{m a} \rightarrow \text{m b} \rightarrow \text{m b}
\end{align*}

While this approach captures the intention of the quantified constraint, it does not enable the type checker to see that \texttt{Monad (t m)} holds for any transformer \texttt{t} and \texttt{m}. While the monad methods are available for \texttt{t m}, they do not have the usual name.

For this reason, Trifonov presents a further (non-Haskell’98) refinement of the encoding, which was adopted by the Monatron [13] library among others. A non-essential difference is that Monatron merges the above \texttt{Monad_t} and \texttt{Trans} into a single class:

\texttt{class MonadT t where}
\begin{align*}
\text{lift} & : \text{Monad m ⇒ m a } \rightarrow \text{t m a} \\
\text{return} & : \text{Monad m} \Rightarrow \text{Monad (t m)}
\end{align*}

The key novelty is that it also makes the methods \texttt{treturn} and \texttt{tbind} available under their usual name with a single \texttt{Monad} instance for all monad transformers.

With these definitions the monad transformer composition does type check. Unfortunately, the head of the \texttt{Monad (t m)} instance is highly generic and easily overlaps with other instances.

The MonadZipper Because they found Monatron’s overlapping instances untenable, Schrijvers and Oliveira [31] presented a different workaround for this problem in the context of their monad zipper datatype, which is an extended form of transformer composition. Their solution adds a method \texttt{mw} to the \texttt{Trans} type class:

\texttt{class Trans t where}
\begin{align*}
lift & : \text{Monad m ⇒ m a } \rightarrow \text{t m a} \\
\text{mw} & : \text{Monad m ⇒ MonadWitness t m}
\end{align*}

8For the implementation see \url{https://hackage.haskell.org/package/Monatron}
For any monad $m$ this method returns a GADT [29] witness for the fact that $t \to m$ is a monad. This is possible because with GADTs, type class instances can be stored in the data constructors.

```haskell
data MonadWitness (t :: (a -> a) -> (a -> a)) m where
  MW :: Monad (t m) => MonadWitness t m
```

By pattern matching on the witness of the appropriate type the programmer can bring the required `Monad (t2 m)` constraint into scope to satisfy the type checker.

```haskell
instance (Trans t1, Trans t2) => Trans (t1 \t2) where
  lift :: ∀m.a. Monad m ⇒ m a → (t1 \t2) m a
  lift = case (mw :: MonadWitness t2 m) of
    MW → C : lift : lift
```

The downside of this approach is that it offloads part of the type checker’s work on the programmer. As a consequence, the code becomes cluttered with witness manipulation.

The constraint Library Kmett’s constraint library [20] provides generic infrastructure for reifying quantified constraints in terms of GADTs, generalizing the MonadZipper solution above. Additionally, it complements the encoding with ample utilities for the manipulation of such constraints. Unfortunately, it suffers from the same problem: passing, construction and deconstruction of dictionaries needs to be manually performed by the programmer.

Corecursive Resolution Fu et al. [6] address the divergence problem that arises for generic nested datatypes. They turn the diverging resolution with user-supplied instances into a terminating resolution in terms of automatically derived instances. These auxiliary instances are derived specifically to deal with the query at hand; they shift the pattern of divergence to the term-level in the form of co-recursively defined dictionaries. The authors do point out that the class of divergent cases they support is limited and that deriving quantified instances would be beneficial.

Cochis The calculus of coherent implicits, COCHIS [32], and its focusing-based resolution in particular, have been a major inspiration of this work. Just like this work, COCHIS supports recursive resolution of quantified constraints. Yet, there are a number of significant differences. Firstly, COCHIS does not feature a separate syntactic sort for type classes, but implicitly resolves regular terms in the Scala tradition. As a consequence, it does not distinguish between instance and superclass axioms, e.g., for the sake of enforcing termination and coherence. Perhaps more significantly, COCHIS features local “instances” as opposed to our globally scoped instances. Local instances may overlap with one another and coherence is obtained by prioritizing those instances that are introduced in the innermost scope. This way COCHIS’s resolution is entirely deterministic, while ours is non-deterministic (yet coherent) due to overlapping local and superclass axioms.

8 Conclusion

This paper has presented a fully fledged design of quantified class constraints. We have shown that this feature significantly increases the modelling power of type classes, while at the same enables a terminating type class resolution for a larger class of applications. Interesting future work we aim to pursue includes (a) establishing the metatheory, (b) extending the system with quantification over predicates, raising the power of type classes to (a fragment of) second-order logic, and (c) studying the interaction of quantified class constraints with commonly used type-level features like functional dependencies [18] or associated type families [3], allowing us to integrate the new feature in Haskell’s ecosystem.

A Additional Judgments

A.1 Well-formedness of Types & Constraints

Well-formedness of types takes the form $\Gamma \vdash \sigma$ and is given by the following rules:

- $a \in \Gamma \quad \Rightarrow \quad TyVar : \Gamma \vdash a$
- $\Gamma \vdash \rho \quad \Rightarrow \quad TyQual : \Gamma \vdash \rho$
- $a \notin \Gamma \quad \Rightarrow \quad C : \Gamma \vdash a, \sigma$

It is entirely straightforward and ensures that type terms are well-formed. Rule `TyQual` requires checking the well-formedness of our new form of constraints $C$, via relation $\Gamma \vdash \Gamma$, given by the following rules:

- $\Gamma \vdash 1 \quad \Rightarrow \quad CQ : (CQ)\Gamma \vdash C1 \quad \Rightarrow \quad C2 \quad \Rightarrow \quad C\Gamma \vdash C1 \Rightarrow C2$
- $\Gamma \vdash C \quad \Rightarrow \quad CV : (CV)\Gamma \vdash C1 \quad \Rightarrow \quad Var\Gamma \vdash C$

Finally, an axiom set $\Gamma$ is well-formed if all constraints it contains are well-formed:

$$\Gamma \vdash AxNil \quad \Gamma \vdash A \quad \Gamma \vdash C \quad \Gamma \vdash A, C$$

A.2 Program Typing

The judgment for program typing takes the form $P; \Gamma \vdash_{pgm} : \sigma$ and is given by the following rules:

- $P; \Gamma \vdash_{pgm} (cls; pgm) : \sigma$
- $P; \Gamma \vdash_{pgm} (inst; pgm) : \sigma$
- $P; \Gamma \vdash_{pgm} e : \sigma$

For brevity, if $P = \bullet$ and $\Gamma = \bullet$ we denote program typing as $\vdash_{pgm} : \sigma$.

A.3 Unification Algorithm

The unification algorithm takes the form $unify(\overline{A}, E) = \theta_\perp$ and is given by the following equations:

- $\overline{\theta} = \bullet$
- $\overline{\theta} = \overline{\theta}$
- $\overline{\theta} = \overline{\theta}$
- $\overline{\theta} = \overline{\theta}$

where $\overline{\theta} = \overline{\theta}$ and $\overline{\theta} = \overline{\theta}$

Function `unify` is a straightforward extension of the standard first-order unification algorithm [5]. The only difference between the two lies in the additional argument: the `untouchable` variables $\overline{A}$.

---

[10] See GHC feature request #5927.
These variables are treated by the algorithm as skolem constants and therefore can not be substituted (they can be unified with themselves though).

### A.4 Elaboration of Programs

Elaboration of programs is given by judgment $\mathcal{P};G;\langle \text{pgm}\rangle : \sigma \rightsquigarrow \text{fpgm}$:

$$\mathcal{P};G;\langle \text{pgm}\rangle : \sigma \rightsquigarrow \text{fpgm}$$

**Program Elaboration**

Rules $\mathcal{P}CS$ and $\mathcal{P}INs$ handle class and instance declarations, respectively, and they are entirely standard. Rule $\mathcal{P}EXP$ performs standard type-inference, simplification [17] and generalization for a top-level expression $e$. For simplicity, we do not utilize interaction rules (e.g. we do not simplify the constraints $\{\text{Eq } a, \text{Ord } a\}$ to $(\text{Ord } a)$, but it is straightforward to do so. Finally, observe that superclass axioms $\mathcal{A}_S$ are not used for the simplification of wanted constraints. This is standard practice for Haskell but our distinction between the axioms within the program theory allows us to express this explicitly.

### B System F Semantics

Both the typing rules and call-by-name operational semantics for System F are entirely standard and can be found elsewhere, we include them here to keep the presentation self-contained. In the following, we denote System F typing environments by $\Delta$:

$$\Delta ::= \bullet \mid \Delta, T \mid \Delta, K : v \mid \Delta, a \mid \Delta, x : v$$

#### B.1 Term Typing

$$\Delta \vdash_{\text{fval}} t : v$$

**Term Typing**

#### B.3 Program Typing

$$\Delta \vdash_{\text{fpgm}} \text{vpgm} : v$$

**Program Typing**

For brevity, if $\Delta = \bullet$ we denote System F program typing as $\nu_{\text{pgm}} : v$.

#### B.4 Value Binding Typing

$$\Delta \vdash_{\text{fval}} \text{fval} : \Delta_{\text{fval}}$$

**Value Binding Typing**

#### B.5 Datatype Declaration Typing

$$\Delta \vdash_{\text{data}} \text{data} : \Delta_{\text{data}}$$

**Datatype Declaration Typing**

#### B.6 Call-by-name Operational Semantics

The small-step, call-by-name operational semantics of System F are presented below:

$$t \rightarrow t'$$

**Operational Semantics (Small-step)**
which has received funding from the European Union’s Horizon 2020 2020 research and innovation programme under grant agreement No 640954.

Acknowledgments

We would like to thank Steven Keuchel, Thomas Winant and Leonidas Lampropoulos, for their constructive feedback. This research was partially supported by the Flemish Fund for Scientific Research (FWO). This work was partially supported by project GRACeFUL, partially supported by the Flemish Fund for Scientific Research for their constructive feedback. This research was partially supported by project GRACeFUL, which has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 640954.

References