# Castor: Programming with Extensible Generative Visitors

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**Abstract**

Much recent work on type-safe extensibility for Object-Oriented languages has focused on design patterns that require modest type system features. Examples of such design patterns include *Object Algebras*, *Extensible Visitors*, *Finally Tagless interpreters*, or *Polymorphic Embeddings*. Those techniques, which often use a functional style, can solve basic forms of the Expression Problem. However, they have important limitations.

This paper presents Castor: a Scala framework for programming with extensible, generative visitors. Castor has several advantages over previous approaches. Firstly, Castor comes with support for (type-safe) pattern matching to complement its visitors with a concise notation to express operations. Secondly, Castor supports type-safe interpreters (à la Finally Tagless), but with additional support for pattern matching and a generally recursive style. Thirdly, Castor enables many operations to be defined using an imperative style, which is significantly more performant than a functional style (especially in the JVM platform). Finally, functional techniques usually only support tree structures well, but graph structures are poorly supported. Castor supports type-safe extensible programming on graph structures. The key to Castor's usability is the use of annotations to automatically generate large amounts of boilerplate code to simplify programming with extensible visitors. To illustrate the applicability of Castor we present several applications and two case studies. The first case study compares the ability of Castor for modularizing the interpreters from the "Types and Programming Languages" book with previous modularization work. The second case study on UML activity diagrams illustrates the imperative aspects of Castor, as well as its support for hierarchical datatypes and graphs.

*Keywords:* modularity, visitor pattern, pattern matching, metaprogramming, OOP

## 1. Introduction

For many years researchers have been looking at improving modularity mechanisms in programming languages. A particular problem that is the focus of much recent work in modularity is the so-called Expression Problem [1]. In the Expression Problem, the key challenge is how to achieve *type-safe extensibility*. That is, how to: evolve software

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in two dimensions (adding new variants and operations) without rewriting existing code; and without using type-unsafe features (such as casts or reflection). Over the years, many solutions were proposed. Some work proposes new programming languages or programming language features designed specifically with modularity in mind. These include *virtual classes* [2], *multi-methods* [3], and *family polymorphism* [4]. Other work has focused on more general language features – such as *generics* [5], *higher-kinded types* [6], *virtual types* [7], *traits* [8] and *mixins* [5] – which can also help with various modularity problems.

Much of the more recent work on type-safe extensibility for Object-Oriented languages focus is on design patterns that require modest type system features. Examples of such design patterns include *Object Algebras* [9], *Modular Visitors* [10], *Finally Tagless interpreters* [11] or *Polymorphic Embeddings* [12]. All of those techniques can solve basic forms of the Expression Problem, and are closely related.

The foundation for a lot of that work comes from functional programming and type-theoretic encodings of datatypes [13, 14]. In particular, the work by Hinze [15] was the precursor for those techniques. In his work Hinze employed so-called Church [13] and Scott [14] encodings of datatypes to model generic programming libraries. Later Oliveira et al. [16, 17] showed that variants of those techniques have wider applications and solve the Expression Problem [1]. These ideas were picked up by Carrete et al. [11] to enable tagless interpreters, while also benefited from the extensibility properties of the techniques. Carrete et al.'s work popularized those applications of the techniques as the nowadays so-called *Finally Tagless* style. Soon after Hofer et al. [12] proposed *Polymorphic Embeddings* in Scala, highly inspired by the Finally Tagless style in languages like Haskell and OCaml.

In parallel with the work on *Finally Tagless* and *Polymorphic Embeddings* the connections of those techniques to the VISITOR pattern in OOP were further explored [18], building on observations between the relationship between type-theoretic encodings of datatypes and visitors by Buchlovsky and Thielecke [19]. That work showed that Church and Scott encodings of datatypes correspond to two variants of the VISITOR pattern called, respectively, *Internal* and *External* visitors. Later on Oliveira and Cook [9] showed a simplified version of *Internal Visitors* called *Object Algebras*, which could solve the Expression Problem even in languages like Java.

While *Internal Visitors*, *Object Algebras*, *Finally Tagless* or *Polymorphic Embeddings* can all be traced back to Church encodings, there has been much less work on techniques that are based on Scott encodings. Scott encodings are more powerful, as they allow a (generally) recursive programming style. In contrast, Church encodings rely on a programming style that is akin to programming with folds in functional programming [20]. In general, Scott encodings require more sophisticated type system features, which is one reason why they have seen less adoption. In particular recursive types are necessary, which also brings up extra complications due to the interaction of recursive types and subtyping. Nevertheless, recent work by Zhang and Oliveira [21] on the Java EVF framework picked up on modular *External Visitors* and shows *External Visitors* can be made practical even with modest language features and code generation. The applicability of EVF is demonstrated by refactoring interpreters from the "Types and Programming Languages" (TAPL) book [22]. The interpreters are modularized, and various specific interpreters are recovered from modular, reusable components. This

effort is non-trivial because TAPL interpreters are written in a small-step operational semantics style, which does not fit well with folds. The fundamental problem is that the recursion pattern for small-step operational semantics is quite different from a fold. Furthermore, many operations employed by implementations of TAPL interpreters depend on other operations. Such *dependencies* are hard to model in a modular setting, but the use of EVF's *External Visitors* can account for them. However, there are still critical limitations on existing type-safe extensibility approaches, including EVF. One drawback is the lack of support for pattern matching, which makes writing various operations quite cumbersome. Another drawback is that even for the techniques that have been adapted to Object-Oriented Programming (OOP), the focus is still on a functional programming style. Writing operations in an imperative style is difficult, and supporting graph structures (which are common in OOP) is nearly impossible.

This paper presents Castor: a Scala framework for programming with extensible, generative visitors. Unlike previous work, Castor aims to support not only a functional style but also an imperative programming style with visitors. Castor visitors bring several advantages over existing approaches:

*Concise Notation.* Programming with the Visitor pattern is typically associated with a lot of boilerplate code. *Extensible Visitors* make the situation even worse due to the heavy use of sophisticated type system features. Although previous work on EVF alleviated the burden of programmers by generating boilerplate code related to visitors and traversals, it is restricted by Java's syntax and annotation processor. Castor improves on EVF by employing Scala's concise syntax and Scalameta[1] to simplify client code. Unlike the Java annotation processor which generates code separately, Scalameta enables direct transformation on the client code, further reducing the boilerplate and hiding sophisticated type system features from users.

*Pattern Matching Support.* Castor comes with support for (type-safe) pattern matching to complement its visitors with a concise notation to express operations. In the OOP context, data structures are open. However, the traditional semantics of pattern matching adopted by many approaches is based on the *order* of patterns, which conflicts with the openness of OO data structures. Therefore, we suggest that a more restricted, top-level pattern matching model, where the order of patterns is irrelevant. To compensate for the absence of ordered patterns we propose a complementary mechanism for case analysis with defaults, which can be used when nested or multiple case analysis is needed. Castor adopts this new pattern matching model. As a result, pattern matching in Castor is concise, exhaustive, extensible and composable.

*GADT-Style Definitions.* Castor supports type-safe interpreters (à la *Finally Tagless*), but with additional support for pattern matching and a generally recursive style. While *Finally Tagless* interpreters are nowadays widely used by programmers in multiple languages (including Haskell and Scala), they must be written in fold-like style. Supporting operations that require nested patterns, or simply depend on other operations is

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[1] http://scalameta.org

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quite cumbersome (although workarounds exist [23]), especially if modularity is to be preserved. In contrast, Castor can support those features naturally.

*Hierarchical Datatypes.* Functional datatypes are typically flat where variants have no relationship with each other. Object-oriented style datatypes, on the other hand, can be hierarchical [24] where datatype constructors can be refined by more specific constructors. Hierarchical datatypes facilitate reuse since the subtyping relation allows the semantics defined for supertypes to be reused for subtypes. Castor exploits OOP features and employs subtyping to model hierarchical datatypes.

*Imperative Traversals.* Castor enables many operations to be defined using an imperative style, which is significantly more performant than a functional style (especially in the JVM platform). Both functional and imperative visitors [19] written with Castor are fully extensible and can later support more variants modularly. Imperative visitors enable imperative style traversals that instead of returning a new Abstract Syntax Tree (AST), modify an existing AST in-place.

*Graph Structures.* Finally functional techniques usually only support tree structures well, but graph structures are poorly supported. Castor supports type-safe extensible programming on graph structures. Compared to trees, graphs are a more general data structure that have many important applications such as common subexpression elimination.

In summary, this paper makes the following contributions:

- **Extensible pattern matching with modular external visitors:** We evaluate existing approaches to pattern matching in an OOP context (Section 2). We show how to incorporate extensible (or open) pattern matching support on modular external visitors, which allows Castor to define non-trivial pattern matching operations.

- **Support for hierarchical datatypes:** Besides flat datatypes that are typically modeled in functional languages, we show how OOP style hierarchical datatypes are supported in Castor (Section 3).

- **Support for GADTs:** We show how to use Castor's support for GADTs in building well-typed interpreters (Section 4), which would be quite difficult to model in a *Finally Tagless* style.

- **Imperative style modular external visitors:** We show how to define imperative style modular external visitors in Castor (Section 5).

- **Support for graph structures:** We show how to do type-safe extensible programming on graph structures, which generalize the typical tree structures in functional programming (Section 5).

- **The Castor framework:** We present a novel encoding for modular pattern matching based on extensible visitors (Section 2.7). The encoding is automated using metaprogramming and the transformation is formalized (Section 6).

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- **Case studies:** We conduct two case studies to illustrate the effectiveness of CASTOR. The first case study on TAPL interpreters (Section 7) demonstrates functional aspects of CASTOR, while the second one on UML activity diagrams (Section 8) demonstrates the object-oriented aspects of CASTOR.

This paper is a significantly extended version of a conference paper [25]. We revise the presentation of the paper and more importantly extend CASTOR with novel features. Firstly, we add a detailed comparison with our previous work on EVF (Section 2.8). Secondly, we improve the way of declaring variants of open datatypes, which enables hierarchical variants (Section 3), GADTs (Section 4), graphs and imperative style visitors (Section 5). Thirdly, we revise the formalization according to the new encoding (Section 6). Finally, we conduct an additional case study on UML activity diagrams (Section 8) for assessing these added features.

Source code for examples, case studies and the CASTOR framework is available at:

https://github.com/wxzh/Castor

## 2. Open Pattern Matching

Pattern matching is a pervasive and useful feature in functional languages (e.g. ML [26] and Haskell [27]) for processing data structures conveniently. Data structures are firstly modeled using algebraic datatypes and then processed through pattern matching. On the other hand, OOP uses class hierarchies instead of algebraic datatypes to model data structures. Still, the same need for processing data structures also exists in OOP. However, there are important differences between data structures modeled with algebraic datatypes and class hierarchies. Algebraic datatypes are typically *closed*, having a fixed set of variants. In contrast, class hierarchies are *open*, allowing the addition of new variants. A closed set of variants facilitates exhaustiveness checking of patterns but sacrifices the ability to add new variants. OO class hierarchies do support the addition of new variants, but without mechanisms similar to pattern matching, some programs are unwieldy and cumbersome to write. In this section, we first characterize four desirable properties of pattern matching in the context of OOP. We then review some of the existing pattern matching approaches in OOP and discuss why they fall in short of the desirable properties. This section ends with an overview of CASTOR and an evaluation summary on the presented approaches.

### 2.1. Desirable Properties of Open Pattern Matching

We identify the following desirable properties for pattern matching in an OOP context:

- **Conciseness.** Patterns should be described concisely with potential support for wildcards, deep patterns, and guards.

- **Exhaustiveness.** Patterns should be exhaustive to avoid runtime matching failure. The exhaustiveness of patterns should be statically verified by the compiler and the missing cases should be reported if patterns are incomplete.

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- **Extensibility.** Datatypes should be extensible in the sense that new data variants can be added while existing operations can be reused without modification or recompilation.

- **Composability.** Patterns should be composable so that complex patterns can be built from smaller pieces. When composing overlapped patterns, programmers should be warned about possible redundancies.

Using these properties as criteria, we next evaluate pattern matching approaches in OOP. We show that many widely used approaches lack some of these properties. We argue that a problem is that many approaches try to closely follow the traditional semantics of pattern matching, which assumes a closed set of variants. Under a closed set of variants, it is natural to use the *order* of patterns to prioritize some patterns over the others. However, when the set of variants is not predefined a priori then relying on some ordering of patterns is problematic, especially if separate compilation and modular type-checking are to be preserved. Nonetheless, many OO approaches, which try to support both an extensible set of variants and pattern matching, still try to use the order of patterns to define the semantics. Unfortunately, this makes it hard to support other desirable properties such as exhaustiveness or composability.

### 2.2. Running Example: ARITH

To facilitate our discussion, a running example from TAPL [22]—an untyped, arithmetic language called ARITH—is used throughout this paper. The syntax and semantics of ARITH are formalized in Figure 1. Our goal is to model the syntax and semantics of ARITH in a concise and modular manner.

ARITH has the following syntactic forms: zero, successor, predecessor, true, false, conditional and zero test. The definition *nv* identifies 0 and successive application of succ to 0 as numeric values. The operational semantics of ARITH is given in *small-step* style, with a set of reduction rules specifying how a term can be rewritten in one step. Repeatedly applying these rules will eventually evaluate a term to a value. There might be multiple rules defined on a single syntactic form. For instance, rules PREDZERO, PREDSUCC and PRED are all defined on a predecessor term. How pred *t* is going to be evaluated in the next step is determined by the shape of the inner term *t*: if *t* is 0, then PREDZERO will be applied; if *t* is a successor application to a numeric value, then PREDSUCC will be applied; otherwise PRED will be applied.

ARITH is a good example for assessing the four properties because: 1) The small-step style semantics is best expressed with a concise *nested case analysis* on terms; 2) ARITH is, in fact, a unification of two sublanguages, NAT (zero, successor and predecessor) and BOOL (true, false, and conditional) plus an extension (zero test). Ideally, NAT and BOOL should be *separately defined* and *modularly reused*.

### 2.3. The VISITOR *Pattern*

The VISITOR design pattern [18] is frequently used to implement interpreters or compilers because of its ability to add new interpretations or compiler phases without modifying the class hierarchy. Let us implement the ARITH language using the VISITOR pattern step by step. The implementation is written in Scala without using any Scala-specific features and can be easily mapped to other OOP languages like C++ or Java.

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$$t \quad ::= \quad 0 \mid \texttt{succ } t \mid \texttt{pred } t \mid \texttt{true} \mid \texttt{false} \mid \texttt{if } t \texttt{ then } t \texttt{ else } t \mid \texttt{iszero } t$$
$$nv \quad ::= \quad 0 \mid \texttt{succ } nv$$

$$\frac{t_1 \rightarrow t_1'}{\texttt{succ } t_1 \rightarrow \texttt{succ } t_1'} \qquad\qquad \frac{}{\texttt{pred } 0 \rightarrow 0}\ \text{PredZero}$$

$$\frac{}{\texttt{pred (succ } nv_1) \rightarrow nv_1}\ \text{PredSucc} \qquad\qquad \frac{t_1 \rightarrow t_1'}{\texttt{pred } t_1 \rightarrow \texttt{pred } t_1'}\ \text{Pred}$$

$$\frac{}{\texttt{if true then } t_2 \texttt{ else } t_3 \rightarrow t_2} \qquad\qquad \frac{}{\texttt{if false then } t_2 \texttt{ else } t_3 \rightarrow t_3}$$

$$\frac{t_1 \rightarrow t_1'}{\texttt{if } t_1 \texttt{ then } t_2 \texttt{ else } t_3 \rightarrow \texttt{if } t_1' \texttt{ then } t_2 \texttt{ else } t_3} \qquad\qquad \frac{}{\texttt{iszero } 0 \rightarrow \texttt{true}}$$

$$\frac{}{\texttt{iszero (succ } nv_1) \rightarrow \texttt{false}} \qquad\qquad \frac{t_1 \rightarrow t_1'}{\texttt{iszero } t_1 \rightarrow \texttt{iszero } t_1'}$$

Figure 1: The syntax and semantics of Arith.

*Abstract Syntax.* The abstract syntax of Arith is modeled by the following class hierarchy:

```scala
215  abstract class Tm {
       def accept[A](v: TmVisit[A]): A
     }
     class TmZero() extends Tm {
       def accept[A](v: TmVisit[A]) = v.tmZero(this)
220  }
     class TmSucc(val t: Tm) extends Tm {
       def accept[A](v: TmVisit[A]) = v.tmSucc(this)
     }
     class TmPred(val t: Tm) extends Tm {
225    def accept[A](v: TmVisit[A]) = v.tmPred(this)
     }
     class TmTrue() extends Tm {
       def accept[A](v: TmVisit[A]): A = v.tmTrue(this)
     }
230  class TmFalse extends Tm {
       def accept[A](v: TmVisit[A]): A = v.tmFalse(this)
     }
     class TmIf(val t1: Tm, val t2: Tm, val t3: Tm) extends Tm {
       def accept[A](v: TmVisit[A]): A = v.tmIf(this)
235  }
     class TmIsZero(val t: Tm) extends Tm {
       def accept[A](v: TmVisit[A]): A = v.tmIsZero(this)
     }
```

The abstract class `Tm` represents the datatype of terms, and syntactic constructs of terms
240 are subclasses of `Tm`. A generic `accept` method is defined throughout the class hierarchy,
which is implemented by invoking the corresponding lowercase *visit method* exposed

by `TmVisit`.

*Visitor Interface.* `TmVisit` is the *visitor interface* that declares all the visit methods required by `accept` implementations. Its definition is given below:

```
245  trait TmVisit[A] {
       def tmZero(x: TmZero): A
       def tmSucc(x: TmSucc): A
       def tmPred(x: TmPred): A
       def tmTrue(x: TmTrue): A
250      def tmFalse(x: TmFalse): A
       def tmIf(x: TmIf): A
       def tmIsZero(x: TmIsZero): A
     }
```

`TmVisit` is parameterized by `A` for abstracting over the return type of visit methods. Each
255  visit method takes an instance of its corresponding class and returns a value of `A`.

*Concrete Visitors.* Operations over `Tm` are *concrete visitors* that implement the visitor interface `TmVisit`. The numeric value checker is defined like this:

```
     class Nv extends TmVisit[Boolean] {
       def tmZero(x: TmZero) = true
260      def tmSucc(x: TmSucc)= x.t.accept(this)
       def tmPred(x: TmPred) = false
       def tmTrue(x: TmTrue) = false
       def tmFalse(x: TmFalse) = false
       def tmIf(x: TmIf) = false
265      def tmIsZero(x: TmIsZero) = false
     }
```

`Nv` implements `TmVisit` by instantiating the type parameter `A` as `Boolean` and giving an implementation to each visit method. Here, the interesting cases are `tmZero` and `tmSucc`. For the former, a `true` is returned; for the latter, we call `_.t.accept(this)` for
270  recursively applying `Nv` to check the inner term. The remaining cases are not numeric values thus return `false`.

With `Nv` defined, we can now implement the small-step evaluation visitor:

```
     class Eval1 extends TmVisit[Tm] {
       val eval1 = this  // Dependency on the visitor itself
275      val nv = new Nv   // Dependency on another visitor
       def tmZero(x: TmZero) = throw NoRuleApplies
       def tmSucc(x: TmSucc) = new TmSucc(x.t.accept(this))
       def tmPred(x: TmPred) = x.t.accept(new TmVisit[Tm] {
         def tmZero(y: TmZero) = y                            // PredZero
280        def tmSucc (y: TmSucc) =
           if (y.t.accept(nv)) y.t                            // PredSucc
           else new TmPred(y.t.accept(eval1))                 // Pred
         def tmPred(y: TmPred) = new TmPred(y.accept(eval1))  // Pred
         def tmTrue(y: TmTrue) = new TmPred(y.accept(eval1))  // Pred
285        def tmFalse(y: TmFalse) = new TmPred(y.accept(eval1))  // Pred
         def tmIf(y: TmIf) = new TmPred(y.accept(eval1))      // Pred
         def tmIsZero(y: TmIsZero) = new TmPred(y.accept(eval1)) // Pred
       })
       def tmTrue(x: TmTrue) = throw NoRuleApplies
290      def tmFalse(x: TmFalse)  = throw NoRuleApplies
       def tmIf(x: TmIf) = x.t1.accept(new TmVisit[Tm] {
```

```
        def tmTrue(y: TmTrue) = x.t2
        def tmFalse(y: TmFalse) = x.t3
        def tmZero(y: TmZero) = new TmIf(y.accept(eval1),x.t2,x.t3)
295     def tmSucc(y: TmSucc) = new TmIf(y.accept(eval1),x.t2,x.t3)
        def tmPred(y: TmPred) = new TmIf(y.accept(eval1),x.t2,x.t3)
        def tmIf(y: TmIf) = new TmIf(y.accept(eval1),x.t2,x.t3)
        def tmIsZero(y: TmIsZero) = new TmIf(y.accept(eval1),x.t2,x.t3)
      })
300   def tmIsZero(x: TmIsZero) = x.t.accept(new TmVisit[Tm] {
        def tmZero(y: TmZero) = new TmTrue
        def tmSucc (y: TmSucc) =
          if (y.t.accept(nv)) new TmFalse
          else new TmIsZero(y.accept(eval1))
305     def tmPred(y: TmPred) = new TmIsZero(y.accept(eval1))
        def tmTrue(y: TmTrue) = new TmIsZero(y.accept(eval1))
        def tmFalse(y: TmFalse) = new TmIsZero(y.accept(eval1))
        def tmIf(y: TmIf) = new TmIsZero(y.accept(eval1))
        def tmIsZero(y: TmIsZero) = new TmIsZero(y.accept(eval1))
310   })
    }
```

The small-step evaluator rewrites a term to another thus A is instantiated as Tm. Since primitive cases are already values, we simply throw a NoRuleApplies exception for tmZero, tmTrue and tmFalse. Defining the case for tmSucc is easy too: we construct a new successor with its inner term rewritten by eval1. In contrast, defining tmPred, tmIf and tmIsZero is trickier because they all have multiple rules. Take tmPred for example. As a visitor recognizes only one level representation of a term, it is insufficient to encode rules that require nested case analysis. To further reveal the shape of the inner term, anonymous visitors are created. Rules like PredSucc can then be specified inside the tmSucc method of the inner visitor. Moreover, the inner visitor of tmPred depends on both Eval1 and Nv. These dependencies are expressed by the fields eval1 and nv, which are instantiated as visitor instances. Then we can pass eval1 or nv as an argument to the accept method for using the dependency. Notice that the Pred rule is repeated 6 times. Similar situations also happen in tmIf and tmIsZero, making the overall implementation of Eval1 quite lengthy.

*Client Code.* We can write some tests for our implementation of Arith:

```
// iszero (if false then true else pred (succ 0))
val tm = new TmIsZero(
  new TmIf(new TmFalse,new TmTrue,new TmPred(new TmSucc(new TmZero))))
330 val eval1 = new Eval1
val tm1 = tm.accept(eval1)  // iszero (pred (succ 0))
val tm2 = tm1.accept(eval1) // iszero 0
val tm3 = tm2.accept(eval1) // 0
```

where we construct a term using all syntactic forms of the Arith language and evaluate it step by step using eval1. The evaluation result of each step is shown in the comments on the right hand side.

*Discussion of the Approach.* The conventional Visitor pattern has been criticized for its *verbosity* and *inextensibility* [28, 29], which are manifested in the implementation of Arith. Programming with the Visitor pattern is associated with a lot of infrastructure

code, including the visitor interface, the class hierarchy, etc. Writing such infrastructure manually is tedious and error-prone, especially when there are many classes involved. Such verbosity restricts the usage VISITOR pattern, as Martin [30] wrote:

> "*Often, something that can be solved with a* VISITOR *can also be solved by something simpler.*"

Moreover, the VISITOR pattern suffers from the Expression Problem [1]: it is *easy* to add new operations by defining new visitors (as illustrated by `nv` and `eval1`) but *hard* to add new variants. The reason is that `Tm` and `TmVisit` are tightly coupled. When trying to add new subclasses to the `Tm` hierarchy, it is not possible to implement their `accept` methods because there exist no corresponding visit methods in `TmVisit`. A non-solution is to modify `TmVisit` with new visit methods. As a consequence, all existing concrete implementations of `TmVisit` have to be modified in order to account for those variants. This violates the "*no modification on existing code*" principle of the Expression Problem. Modification is even impossible if the source code is unavailable. As a result, NAT and BOOL cannot be separated from ARITH. Thus, the whole implementation is neither extensible nor composable. Nevertheless, the exhaustiveness on visit methods is guaranteed since a class cannot contain any abstract methods.

### 2.4. Sealed Case Classes

The VISITOR pattern is often used as a poor man's approach to pattern matching in OO languages. Fortunately, Scala [31] is a language that unifies functional and OO paradigms and supports pattern matching natively via case classes/extractors [32]. Case classes can be either open or sealed. Sealed case classes are close to algebraic datatypes in functional languages, which have a fixed set of variants.

Representing the `Tm` hierarchy using sealed case classes looks like this:

```scala
sealed trait Tm
case object TmZero extends Tm
case class TmSucc(t: Tm) extends Tm
case class TmPred(t: Tm) extends Tm
case object TmTrue extends Tm
case object TmFalse extends Tm
case class TmIf(t1: Tm, t2: Tm, t3: Tm) extends Tm
case class TmIsZero(t: Tm) extends Tm
```

The differences are that `Tm` is a `sealed trait` and variants of `Tm` are additionally marked as `case`. Also, no-argument variants are Scala's singleton `object`s and fields of case classes are by default `val`.

The `case` keyword triggers the Scala compiler to automatically inject methods into a class, including a constructor method (`apply`) and an extractor method (`unapply`). The injected constructor method simplifies creating objects from case classes. For example, a successor application to zero can be constructed via `TmSucc(TmZero)`. Conversely, the injected extractor enables tearing down an object via pattern matching.

The numeric value checker can be defined by pattern matching on the term:

```scala
def nv(t: Tm): Boolean = t match {
  case TmZero => true
  case TmSucc(t1) => nv(t1)
  case _ => false
}
```

The term `t` is matched sequentially against a series of patterns (`case` clauses). For example, `TmSucc(TmZero)` will be handled by the second `case` clause of `nv`, which recursively invokes `nv` on its subterm `t1` (which is `TmZero`). Then, `TmTrue` will be matched by the first `case` clause with a `true` returned eventually. A *wildcard pattern* (`_`) is used in the last `case` clause for handling boring cases altogether.

The strength of pattern matching shines in encoding the small-step semantics:

```
def eval1(t: Tm): Tm = t match {
  case TmSucc(t1) => TmSucc(eval1(t1))
  case TmPred(TmZero) => TmZero            // PredZero
  case TmPred(TmSucc(t1)) if nv(t1) => t1  // PredSucc
  case TmPred(t1) => TmPred(eval1(t1))     // Pred
  case TmIf(TmTrue,t2,_) => t2
  case TmIf(TmFalse,_,t3) => t3
  case TmIf(t1,t2,t3) => TmIf(eval1(t1),t2,t3)
  case TmIsZero(TmZero) => TmTrue
  case TmIsZero(TmSucc(t1)) if nv(t1) => TmFalse
  case TmIsZero(t1) => TmIsZero(eval1(t1))
  case _ => throw NoRuleApplies
}
```

With the help of pattern matching, the overall definition is a direct mapping from the formalization shown in Figure 1. There is a one-to-one correspondence between the rules and the case clauses. For example, PREDSUCC is concisely described by a *deep* pattern (`TmPred(TmSucc(t1))`) with a *guard* (`if nv(t1)`) and PRED is captured only once by `TmPred(t1)`.

*Client Code.* The client code is also more natural and compact than that in visitors:

```
val tm = TmIsZero(TmIf(TmFalse,TmTrue,TmPred(TmSucc(TmZero))))
val tm1 = eval1(tm)  // iszero (pred (succ 0))
val tm2 = eval1(tm1) // iszero 0
val tm3 = eval1(tm2) // 0
```

where `new` clauses are no longer needed.

*Discussion of the Approach.* The ARITH implementation using sealed case classes is very concise. Moreover, sealed case classes facilitate exhaustiveness checking on patterns since all variants are statically known. If we forgot to write the wildcard pattern in `nv`, the Scala compiler would warn us that a `case` clause for `TmPred` is missing. An exception is `eval1`, whose exhaustiveness is not checked by the compiler due to the use of guards. The reason is that a guard might call some function whose execution result is only known at runtime, making the reachability of that pattern difficult to decide statically. The price to pay for exhaustiveness is the inability to add new variants of `Tm` in separate files. Thus, like the visitor version, the implementation is neither extensible nor composable.

### 2.5. Open Case Classes

While the implementation using sealed case classes is concise, it is not modular because ARITH is still defined as a whole. To separate out NAT and BOOL, we turn to open case classes by trading exhaustiveness checking for the ability to add new variants in separate files. To make up for the loss of exhaustiveness, Zenger and Odersky's idea

of *Extensible Algebraic Datatypes with Defaults* (EADDs) [33] can be applied. The key idea is to always use a default in each operation to handle variants that are not explicitly mentioned. The existence of a default makes operations extensible, as variants added later will be automatically subsumed by that default. If the extended variants have behavior different from the default, we can define a new operation that deals with the extended variants and delegates to the old operation.

We first remove the `sealed` constraint on `Tm` and specify the default behavior of `eval1` inside a trait `Term`:

```
trait Term {
  trait Tm
  def eval1(t: Tm): Tm = throw NoRuleApplies
}
```

Then, Nat can be defined as an extended trait for `Term`:

```
trait Nat extends Term {
  case object TmZero extends Tm
  case class TmSucc(t: Tm) extends Tm
  case class TmPred(t: Tm) extends Tm
  def nv(t: Tm): Boolean = t match {
    case TmZero => true
    case TmSucc(t1) => nv(t1)
    case _ => false
  }
  override def eval1(t: Tm): Tm = t match {
    case TmSucc(t1) => TmSucc(eval1(t1))
    case TmPred(TmZero) => TmZero          // PredZero
    case TmPred(TmSucc(t1)) if nv(t1) => t1 // PredSucc
    case TmPred(t1) => TmPred(eval1(t1))    // Pred
    case _ => super.eval1(t)
  }
}
```

`Nat` introduces `TmZero`, `TmSucc` and `TmPred` as variants of `Tm`. `nv` is defined in the old way. `eval1` is overridden with case clauses for `TmSucc` and `TmPred`, and `TmZero` is dealt by `Term`'s `eval1` via a `super` call.

Similarly, Bool is defined as another trait that extends `Tm` with its own variants and `eval1`:

```
trait Bool extends Tm {
  case object TmTrue extends Tm
  case object TmFalse extends Tm
  case class TmIf(t1: Tm,t2: Tm,t3: Tm) extends Tm
  override def eval1(t: Tm): Tm = t match {
    case TmIf(TmTrue,t2,_) => t2
    case TmIf(TmFalse,_,t3) => t3
    case TmIf(t1,t2,t3) => TmIf(eval1(t1),t2,t3)
    case _ => super.eval1(t)
  }
}
```

Finally, Arith can be defined as a unification of Nat and Bool implementations:

```
trait Arith extends Nat with Bool {
  case class TmIsZero(t: Tm) extends Tm
  override def eval1(t: Tm) = t match {
    case TmIsZero(TmZero) => TmTrue
```

```
      case TmIsZero(TmSucc(t1)) if nv(t1) => TmFalse
      case TmIsZero(t1) => TmIsZero(eval1(t1))
      case TmZero => super[Nat].eval1(t)
485   case _: TmSucc => super[Nat].eval1(t)
      case _: TmPred => super[Nat].eval1(t)
      case _ => super[Bool].eval1(t)
   }
}
```

Scala's *mixin composition* allows `Arith` to extend both `Nat` and `Bool`. The definition `nv`
inherited from `Nat` works well in `Arith`, as it happens to have a very good default that
automatically fits for the new cases. For instance, calling `nv(TmFalse)` returns `false`
as expected. However, overridding `eval1` becomes problematic. We cannot simply
complement the cases for `TmIsZero` and handle all the inherited cases at once since
both `Nat` and `Bool` are extended. Instead we have to separate the inherited cases using
*typecases* and delegate appropriately to either `Nat` or `Bool` via `super` calls.

*Discussion of the Approach.* Combining open case classes with EADDs brings exten-
sibility. This idea works well for *linear* extensions (such as NAT and BOOL) but not so
well for *non-linear* extensions like ARITH. As shown by `eval1` in `Arith`, composing
non-linear extensions is tedious and error-prone. Without any assistance from the Scala
compiler during this process, it is rather easy to make mistakes like forgetting to delegate
a case or delegating a case to a wrong parent. Moreover, the exhaustiveness checking
on case clauses is lost. Although in the spirit of EADDs case clauses should always end
with a wildcard that ensures exhaustiveness, it is not enforced by the Scala compiler.

### 2.6. Partial Functions

To ease the composition of `Nat` and `Bool`, one may consider Scala's `PartialFunction`.
`PartialFunction` provides an `orElse` method for composing partial functions. `orElse`
tries the composed partial functions sequentially until no `MatchError` is raised.

The open case class version of ARITH can be adapted to a partial function version
with a few changes. First, `eval1` in `Term` should be declared as a partial function:

```
def eval1: PartialFunction[Tm,Tm]
```

Second, wildcards cannot be used in implementing `eval1` anymore because they will
shadow other partial functions to be composed. For example, `eval1` in `Bool` is rewritten
as:

```
override def eval1 {
   case TmIf(TmTrue,t2,_) => t2
   case TmIf(TmFalse,_,t3) => t3
   case TmIf(t1,t2,t3) => TmIf(eval1(t1),t2,t3)
   case TmTrue => throw NoRuleApplies
   case TmFalse => throw NoRuleApplies
}
```

An instance of `PartialFunction[Tm,Tm]` is constructed using the anonymous function
syntax with the argument `Tm` being directly pattern matched. The wildcard pattern is
replaced by two constructor patterns `TmTrue` and `TmFalse` with identical right hand side,
losing some convenience. Nevertheless, partial functions make the composition work
more smoothly, avoiding the problems caused by the open case classes approach:

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```scala
override def eval1 = super[Nat].eval1 orElse super[Bool].eval1 orElse {
  case TmIsZero(TmZero) => TmTrue
  case TmIsZero(TmSucc(t1)) if nv(t1) => TmFalse
  case TmIsZero(t1) => TmIsZero(eval1(t1))
}
```

eval1 is overridden by chaining eval1 from `Nat` and `Bool` as well as a new partial function for the zero test using the `orElse` combinator.

*Discussion of the Approach.* Although combining open case classes with partial functions makes the composition smoother, it is still not fully satisfactory. The `orElse` combinator is left-biased, thus the *composition order determines the composed semantics*. That is, `f orElse g` is not equivalent to `g orElse f`, if `f` and `g` are two overlapped partial functions (i.e. containing `case` clauses with identical left hand side but different right hand side). When composing such overlapped partial functions, `orElse` gives no warning. Also, the semantics of the overlapped patterns are all from either `f` or `g`, depending on which comes first. It is not possible to have a mixed semantics for overlapped patterns (e.g. picking `case` A from `f` and `case` B from g when both `f` and g define `case` A and `case` B), which restricts the reusability of partial functions. Lastly, partial functions rely on exception handling, which has a negative impact on performance.

### 2.7. Extensible Visitors

Essentially what makes pattern matching hard to be extended or composed is the *order-sensitive* semantics of pattern matching and wildcard patterns that cover both known and unknown variants. We think it is useful to distinguish between top-level (shallow) patterns and nested (deep) patterns. Top-level patterns should be order-insensitive and partitioned into multiple definitions so that they can be easily composed. We can achieve this by combining open case classes with extensible visitors [34, 10, 35, 21].

The ARITH implementation is organized in a way similar to the open case classes approach. Let us start with `Term`:

```scala
trait Term {
  type TmV <: TmVisit
  trait Tm { def accept(v: TmV): v.OTm }
  trait TmVisit { _: TmV =>
    type OTm
    def apply(t: Tm) = t.accept(this)
  }
  trait TmDefault extends TmVisit { _: TmV =>
    def tm: Tm => OTm
  }
  trait Eval1 extends TmDefault { _: TmV =>
    type OTm = Tm
    def tm = _ => throw NoRuleApplies
  }
  val eval1: Eval1
}
```

Instead of using `TmVisit` in declaring the `accept` method, we use an *abstract type member* `TmV` and constrain it to be a *subtype* of `TmVisit`. This enables invocations on the methods declared inside `TmVisit`, but at the same time, decouples `Tm` from

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`TmVisit`. The upper bound of the return type of the visit methods is also captured by
an abstract type rather than a type parameter for avoiding reinstantiation in inherited
visitors. Accordingly, the return type of `accept` is now a path dependent type `v.OTm`. A
syntactic sugar method `apply` is defined inside `TmVisit` for enabling `v(x)` as a shorthand
of `x.accept(v)`, where x and v are instances of `Tm` and `TmVisit`, respectively. To pass
`this` as an argument of `accept` in implementing `apply`, we state that `TmVisit` is of type
`TmV` using a *self-type annotation*. To mimic wildcards, we use default visitors [36].
But unlike wildcards, default visitors only deal with *known* variants. `TmDefault` is the
default visitor interface, which extends `TmVisit` with a generic `tm` method for specifying
the default behavior. `Eval1` is a default visitor thus it extends `TmDefault`, specifies the
output type `OTm` as `Tm` and implements `tm`. Each concrete visitor has a companion `val`
declaration for allowing themselves to be used in other visitors.

The encoding makes more sense with the implementation of `Nat` given:

```scala
trait Nat extends Term {
  type TmV <: TmVisit
  case object TmZero extends Tm {
    def accept(v: TmV): v.OTm = v.tmZero
  }
  case class TmSucc(t: Tm) extends Tm {
    def accept(v: TmV): v.OTm = v.tmSucc(t)
  }
  case class TmPred(t: Tm) extends Tm {
    def accept(v: TmV): v.OTm = v.tmPred(t)
  }
  trait TmVisit extends super.TmVisit { _: TmV =>
    def tmZero: OTm
    def tmSucc: TmSucc => OTm
    def tmPred: TmPred => OTm
  }
  trait TmDefault extends TmVisit with super.TmDefault { _: TmV =>
    def tmZero = tm(TmZero)
    def tmSucc = tm
    def tmPred = tm
  }
  def nv(t: Tm): Boolean = t match {
    case TmZero => true
    case TmSucc(t1) => nv(t1)
    case _ => false
  }
  trait Eval1 extends TmDefault with super.Eval1 { _: TmV =>
    override def tmSucc = x => TmSucc(this(x.t))
    override def tmPred = {
      case TmPred(TmZero) => TmZero
      case TmPred(TmSucc(t)) if nv(t) => t
      case TmPred(t) => TmPred(this(t))
    }
  }
}
```

`Tm` is extended with several case classes/objects. Correspondingly `TmVisit` is extended
with new visit methods and `TmV` is *covariantly refined* as the subtype of the extended
`TmVisit`. Visit methods are declared using Scala's functions instead of ordinary methods

for two reasons. First, the argument type (e.g. `TmSucc`) has already been revealed by the method name (`tmSucc`) and can be inferred by the Scala compiler without losing information. Second, first-class functions facilitate pattern matching on the argument. These two advantages result in a concise definition of `Eval1`, where the type of `x` is omitted and a value of `TmPred => Tm` is constructed by pattern matching. Unlike conventional visitors, nested case analysis is much simplified via (nested) pattern matching rather than auxiliary visitors. For example, when a predecessor term is processed by `Eval1`, it will be recognized and dispatched to the `tmPred` method. Then the `TmPred` object is matched by the `case` clauses. As these are `case` clauses, deep patterns and guards can be used. To restore the convenience of wildcards for top-level patterns, `TmDefault` is used, which implements visit methods by delegating to `tm`. Notice that `Eval1` is defined as a trait instead of a class for enabling mixin composition. By extending both `TmDefault` and `super.Eval1`, `Eval1` only needs to override interesting cases.

The numeric value checker is defined as a method rather than a visitor. This is because, as we have discussed, *nv* is a good candidate for applying EADDs. Of course, *nv* can be defined as a default visitor like `Eval1`. But whenever `Nat` is extended with new terms, the definition of *nv* has to be refined by composing `Nv` with the extended `TmDefault`.

Bool is defined in a similar manner:

```scala
trait Bool extends Term {
  type TmV <: TmVisit
  trait TmVisit extends super.TmVisit { _: TmV =>
    def tmTrue: OTm
    def tmFalse: OTm
    def tmIf: TmIf => OTm
  }
  trait TmDefault extends TmVisit with super.TmDefault { _: TmV =>
    def tmTrue = tm(TmTrue)
    def tmFalse = tm(TmFalse)
    def tmIf = tm
  }
  case object TmTrue extends Tm {
    override def accept(v: TmV) = v.tmTrue
  }
  case object TmFalse extends Tm {
    override def accept(v: TmV) = v.tmFalse
  }
  case class TmIf(t1: Tm, t2: Tm, t3: Tm) extends Tm {
    override def accept(v: TmV) = v.tmIf(this)
  }
  trait Eval1 extends TmDefault with super.Eval1 { _: TmV =>
    override def tmIf = {
      case TmIf(TmTrue,t2,_) => t2
      case TmIf(TmFalse,_,t3) => t3
      case TmIf(t1,t2,t3) => TmIf(this(t1), t2, t3)
    }
  }
}
```

With case clauses partitioned into visit methods according to their top-level pattern,

unifying `Nat` and `Bool` becomes easy via Scala's mixin composition:

```scala
trait Arith extends Nat with Bool {
  type TmV <: TmVisit
  case class TmIsZero(t: Tm) extends Tm {
    override def accept(v: TmV) = v.tmIsZero(this)
  }
  trait TmVisit extends super[Nat].TmVisit
               with super[Bool].TmVisit { _: TmV =>
    def tmIsZero: TmIsZero => OTm
  }
  trait TmDefault extends TmVisit with super[Nat].TmDefault
                  with super[Bool].TmDefault { _: TmV =>
    def tmIsZero = tm
  }
  trait Eval1 extends TmVisit with super[Nat].Eval1
              with super[Bool].Eval1 { _: TmV =>
    def tmIsZero = {
      case TmIsZero(TmZero) => TmTrue
      case TmIsZero(TmSucc(t)) if nv(t) => TmFalse
      case TmIsZero(t) => TmIsZero(this(t))
    }
  }
}
```

Defining `Eval1` for `Arith` only needs to inherit `Eval1` definitions from `Nat` and `Bool` and complement the `tmIsZero` method. Since `tmIsZero` is an interesting case, `Eval1` extends `TmVisit` rather than `TmDefault`.

*Instantiation.* Components defined in this way cannot be directly used in client code. An additional step to instantiate traits into objects is required. Instantiating `Arith`, for example, is done like this:

```scala
object Arith extends Arith {
  type TmV = TmVisit
  object eval1 extends Eval1
}
```

The companion object `Arith` binds the abstract type `TmV` to its corresponding the visitor interface `TmVisit`. The `eval1` declaration is met by a singleton object that extends `Eval1`. If `Eval1` does not implement all the visit methods, the object creation fails, with the missing methods reported.

*Client Code.* Now we can use the companion object `Arith` in client code:

```scala
import Arith._
val tm = TmIsZero(TmIf(TmFalse,TmTrue,TmPred(TmSucc(TmZero))))
val tm1 = eval1(tm)  // iszero (pred (succ 0))
val tm2 = eval1(tm1) // iszero 0
val tm3 = eval1(tm2) // 0
```

By importing `Arith`, the constructors and visitors defined inside `Arith` are in scope. With the syntactic sugar defined for visitors, a term can be constructed and evaluated identically to the case class version.

*Discussion of the Approach.* With the powerful extensible visitor encoding, the ARITH implementation is made both extensible and composable. However, extensible visitors

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are even more verbose than conventional ones. The use of traits in implementing visitors brings composability but, at the same time, requires extra instantiation code. Another downside of using traits is that the exhaustiveness checking on visit methods is deferred to the instantiation stage. Moreover, the encoding relies on advanced features of Scala, making it less accessible to novice Scala programmers.

### 2.8. EVF

Programming with visitors can be greatly simplified with the associated infrastructure automatically generated. This idea has been adopted in our previous work on EVF [21], which employs Java annotation processors for generating extensible visitor infrastructure.

EVF employs Object Algebra interfaces [9] to describe the abstract syntax:

```java
@Visitor interface TmAlg<Tm> {
  Tm TmZero();
  Tm TmSucc(Tm t);
  Tm TmPred(Tm t);
}
```

where the type parameter `Tm` represents the datatype and capitalized methods that return `Tm` represent variants of `Tm`. Annotated as `@Visitor`, `TmAlg` will be recognized and processed by EVF. Then the infrastructure for `TmAlg` will be generated, including a class hierarchy, a visitor interface and various default visitors. Based on the generated visitor infrastructure, we are able to implement `Nv`:

```java
interface Nv<Tm> extends TmAlgDefault<Tm,Boolean> {
  @Override default Zero<Boolean> m() {
    return () -> false;
  }
  default Boolean TmZero() {
    return true;
  }
  default Boolean TmSucc(Tm t) {
    return visitTm(t);
  }
}
```

`Nv` is defined as an interface with visit methods implemented using default methods for retaining composability. The Java extensible visitor encoding adopted by EVF is, however, not as powerful as the Scala one shown in Section 2.7, which does not support modular ASTs. Whenever an annotated Object Algebra interface gets extended, a new class hierarchy is generated. Thus, we cannot refer to a concrete datatype directly in visitors since this will make them inextensible. Instead, datatypes are kept abstract in visitors. To traverse an abstract datatype like `Tm`, `visitTm` is called. `visitTm` is a method exposed by the generated visitor interface, similar to `apply` shown in Section 2.7. `TmAlgDefault` is the default visitor similar to `TmDefault`, where the default behavior is specified inside `m()`.

Defining `Eval1` is tricker:

```java
interface Eval1<Tm> extends TmAlgDefault<Tm,Tm>, tm.Eval1<Tm> {
  TmAlgMatcher<Tm,Tm> matcher();  // Dependency for nested case analysis
  TmAlg<Tm> f();                  // Dependency for AST reconstruction
  Nv<Tm> nv();                    // Dependency for another visitor
```

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```
770    @default Tm TmPred(Tm t) {
         return matcher()
            .TmZero(() -> t)
            .TmSucc(t1 -> nv().visitTm(t1) ? t1 : TmPred(visitTm(t)))
            .otherwise(() -> f().TmPred(visitTm(t)))
775         .visitTm(t);
       }
       default Tm TmSucc(Tm t) {
         return f().TmSucc(visitTm(t));
       }
780    }
```

There are three dependencies declared using abstract methods. Firstly, since Java does not support native pattern matching, the `matcher` dependency is convenient for constructing anonymous visitors. `matcher` returns an instance of the generated `TmAlgMatcher` interface, which provides fluent setters for defining visit methods via Java 8's lambdas. The `otherwise` setter mimics the wildcard pattern. Secondly, the reconstruction of a term is done via an abstract factory `f` of type `TmAlg<Tm>`. Lastly, the abstract method `nv` expresses the dependency on the visitor `Nv`.

Boo is implemented similarly in another package `bool`, whose definition is omitted. The implementation of Arith is more interesting, which is shown below:

```
790    @Visitor interface TmAlg<Tm> extends nat.TmAlg<Tm>, bool.TmAlg<Tm> {
         Tm TmIsZero(Tm t);
       }
       interface Eval1<Tm> extends GTmAlg<Tm,Tm>,bool.Eval1<Tm>,nat.Eval1<Tm> {
         TmAlgMatcher<Tm,Tm> matcher(); // Dependency refinement
795      TmAlg<Tm> f();                 // Dependency refinement
         default Tm TmIsZero(Tm t) {
           return matcher()
             .TmZero(() -> f().TmTrue())
             .TmSucc(t1 -> nv(t1) ? f().TmFalse() : f().TmIsZero(visitTm(t)))
800         .otherwise(() -> f().TmIsZero(visitTm(t)))
             .visitTm(t);
         }
       }
       interface Nv<Tm> extends TmAlgDefault<Tm,Boolean>, nat.Nv<Tm> {}
```

Nat and Boo implementations are merged using Java 8' multiple interface inheritance. Despite complementing `TmIsZero`, return types of dependencies are covariantly refined for allowing `TmIsZero` calls. Since `Nv` is implemented as a visitor, it needs to be refined as well.

*Instantiation.* Instantiating interfaces into classes for creating objects is also required:

```
810    static class NvImpl implements Nv<CTm>, TmAlgVisitor<Boolean> {}
       static class Eval1Impl implements Eval1<CTm>, TmAlgVisitor<CTm> {
         public TmAlg<CTm> f() { return f; }
         public TmAlgMatcher<CTm,CTm> matcher() {
           return new TmAlgMatcherImpl<>();
815      }
         public Nv<CTm> nv() { return nv; }
       }
       static TmAlgFactory f = new TmAlgFactory();
       static NvImpl nv = new NvImpl();
820    static Eval1Impl eval1 = new Eval1Impl();
```

The interfaces are instantiated into classes with a suffix `Impl`. `Eval1Impl`, for example, implements `Eval1` by: 1) instantiating `Tm` as the generated datatype `CTm`; 2) inheriting the generated `TmAlgVisitor` for a `visitTm` implementation; 3) fullfilling the dependencies using `TmAlgFactory`, `TmAlgMatcherImpl` and `NvImpl` respectively.

*Client Code.* The term is constructed via the factory object `f` and can be evaluated like this:

```
CTm tm = f.TmIsZero(
  f.TmIf(f.TmFalse(),f.TmTrue(),f.TmPred(f.TmSucc(f.TmZero())))));
eval1.visitTm(eval1.visitTm(eval1.visitTm(tm)))
```

*Discussion of the Approach.* EVF simplifies programming with visitors through code generation. It further addresses the extensibility issue by adopting extensible visitors. Restricted by Java, nested case analysis in EVF is done by means of anonymous visitors, which is not as expressive and concise as pattern matching in Scala. To enable composability, EVF visitors are defined using Java 8's interfaces with default methods— in the same spirit of using traits in Scala. Consequently, the exhaustiveness checking on the top-level visit methods is lost in visitor definition site and is delayed to the visitor instantiation site. Nevertheless, the exhaustiveness on the visit methods of the anonymous visitors is guaranteed because the `otherwise` setter must be called when constructing an anonymous visitor.

## 2.9. CASTOR

Highly inspired by EVF, CASTOR is a Scala framework designed for programming with generative, extensible visitors. CASTOR improves on EVF in two aspects. First, CASTOR adopts a more powerful Scala extensible visitor encoding presented in Section 2.7 that additionally enables pattern matching, GADTs, hierarchical datatypes, graphs, etc. Second, CASTOR employs Scalameta for annotation processing, which allows not only generating new code based on the annotated code but also modifying the annotated code itself. These extra abilities together result in more concise and expressive visitor code than that in EVF. We next give a modular implementation of ARITH using CASTOR, which has a one-to-one correspondence with the code shown in Section 2.7.

Let us start with the root component `Term`:

```
@family trait Term {
  @adt trait Tm
  @default(Tm) trait Eval1 {
    type OTm = Tm
    def tm = _ => throw NoRuleApplies
  }
}
```

Several CASTOR's annotations are employed: `@family` denotes a CASTOR's component; `@adt` denotes a datatype; `@default(Tm)` denotes a default visitor on `Tm`. Compared to the `Term` definition shown in Section 2.7, the definition here is much simplified. The `accept` declaration, the type member `TmV`, the visitor interface `TmVisit` and the default visitor `TmDefault` are all generated by analyzing the `@adt` definition of `Tm`. Similarly, CASTOR adds the extends clause, the self type annotation and the corresponding `val` declaration for `Eval1` by the annotation `@default(Tm)`.

Defining `Nat` is also much simplified:

```
     @family trait Nat extends Term {
       @adt trait Tm extends super.Tm {
         case object TmZero
         case class TmSucc(t: Tm)
870      case class TmPred(t: Tm)
       }
       def nv(t: Tm): Boolean = t match {
         case TmZero => true
         case TmSucc(t1) => nv(t1)
875      case _ => false
       }
       @default(Tm) trait Eval1 extends super.Eval1 {
         override def tmSucc = x => TmSucc(this(x.t))
         override def tmPred = {
880        case TmPred(TmZero) => TmZero
           case TmPred(TmSucc(t)) if nv(t) => t
           case TmPred(t) => TmPred(this(t))
         }
       }
885  }
```

Variants of `Tm` are declared inside `Tm`. CASTOR will pull them outside of `Tm` and automatically complement the `extends` clause and the `accept` method definition. Since new variants of `Tm` are introduced, CASTOR will add the extended `TmVisit`, `TmDefault` and refined `TmV` to `Nat`.

Similarly, BOOL can be defined as follows:

```
     @family trait Bool extends Term {
       @adt trait Tm extends super.Tm {
         case object TmTrue
         case object TmFalse
895      case class TmIf(t1: Tm, t2: Tm, t3: Tm)
       }
       @default(Tm) trait Eval1 extends super.Eval1 {
         override def tmIf = {
           case TmIf(TmTrue,t2,_) => t2
900        case TmIf(TmFalse,_,t3) => t3
           case TmIf(t1,t2,t3) => TmIf(this(t1),t2,t3)
         }
       }
     }
```

The code below finishes the ARITH implementation:

```
     @family trait Arith extends Nat with Bool {
       @adt trait Tm extends super[Nat].Tm with super[Bool].Tm {
         case class TmIsZero(t: Tm)
       }
910  @visit(Tm) trait Eval1 extends super[Nat].Eval1
                           with super[Bool].Eval1 {
         def tmIsZero = {
           case TmIsZero(TmZero) => TmTrue
           case TmIsZero(TmSucc(t)) if nv(t) => TmFalse
915        case TmIsZero(t) => TmIsZero(this(t))
         }
       }
     }
```

Since the `TmIsZero` is an interesting case for `Eval1`, `@visit` annotation is used, which denotes an ordinary visitor. Thus, `Eval1` extends `TmVisit` after transformation.

*Client Code.* A `@family` trait can be directly imported in client code since CASTOR automatically generates a companion object for it:

```
import Arith._
val tm = TmIsZero(TmIf(TmFalse,TmTrue,TmPred(TmSucc(TmZero))))
val tm1 = eval1(tm) // iszero (pred (succ 0))
val tm2 = eval1(tm1) // iszero 0
val tm3 = eval1(tm2) // 0
```

which is identical to the client code for Scala extensible visitors shown in Section 2.7.

*Discussion of the Approach.* We discuss how CASTOR addresses the four properties:

- **Conciseness.** By employing Scala's concise syntax and metaprogramming, CASTOR greatly simplifies the definition and usage of visitors. In particular, the need for auxiliary visitors in performing deep case analysis is now replaced by pattern matching via `case` clauses. The concept of visitors is even made transparent to the end-user, making the framework more user-friendly.

- **Exhaustiveness.** The exhaustiveness of patterns in CASTOR consists of two parts. The exhaustiveness of visit methods is checked by the Scala compiler when generating companion objects. For nested patterns using `case` clauses, a default must be provided. However, this default is neither statically enforced by Scala nor CASTOR. Note, however, that with specialized language support it is possible to enforce that nested patterns always provide a default. This is precisely what EADDs [33] do.

- **Extensibility.** As illustrated by `Nat`, `Bool` and `Arith`, we can extend the datatype with new variants and operations, modularly. Such extensibility is enabled by the underlying extensible visitor encoding.

- **Composability.** CASTOR obtains composability via Scala's mixin composition, as illustrated by `Arith`. Unlike partial functions, which silently compose overlapped patterns, composing overlapped patterns in CASTOR will trigger compilation errors because they are conflicting methods from different traits. The error message will indicate the source of conflicts and we are free to select an implementation in resolving the conflict. The composition order does not matter as well.

Table 1 summarizes the evaluation on pattern matching approaches abovementioned in terms of conciseness, exhaustiveness, extensibility, and composability. CASTOR is compared favorably in terms of the four properties among the approaches.

### 3. Hierarchical Datatypes

Traditional functional style datatypes are *flat*: variants have no relationships among each other. In contrast, object-oriented style datatypes (i.e. data structures modeled as class hierarchies) can be *hierarchical*: a variant can extend intermediate datatypes

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Table 1: Pattern matching support comparison: ●= good, ◐= neutral, ○= bad.

| | Conciseness | Exhaustiveness | Extensibility | Composability |
|---|:---:|:---:|:---:|:---:|
| Conventional visitors | ○ | ● | ○ | ○ |
| Sealed case classes | ● | ● | ○ | ○ |
| Open case classes | ● | ○ | ● | ○ |
| Partial functions | ● | ○ | ● | ◐ |
| Extensible visitors | ○ | ○ | ● | ● |
| EVF | ◐ | ◐ | ● | ● |
| Castor | ● | ◐* | ● | ● |

> \* Castor only gets half score on exhaustiveness because *for nested case analysis Scala cannot enforce a default*. In a language-based approach nested case analysis should always require a default, thus fully supporting exhaustiveness.

and/or an existing variant. In other words, while OO style class hierarchies can be arbitrarily deep, typical functional datatypes would correspond to a hierarchy where the depth is always one.

Hierarchical datatypes facilitate reuse. The subtyping relation allows the semantics defined for supertypes to be reused in subtypes. Castor supports both styles of datatypes. In this section, we illustrate Castor's support for hierarchical datatypes by revising the Arith language. Another form of hierarchical datatypes will be shown in Section 5, where a new variant is introduced by refining an existing variant. Moreover, the case study on UML Activity Diagrams Section 8 further illustrates the application of hierarchical datatypes.

### 3.1. Flat Datatypes versus Hierarchical Datatypes

Terms of the Arith language shown in Section 2 are represented as a flat datatype, where all the variants extend the root datatype Tm. In fact, terms can be organized in a hierarchical manner according to their types and arities. Figure 2 visualizes the hierarchical representation of terms and the following code materializes it using Castor:

```
@adt trait Tm {
  trait TmNullary
  trait TmUnary { val t: Tm }
  trait TmTernary { val t1, t2, t3: Tm }
  trait TmNat extends TmNullary
  trait TmBool extends TmNullary
  trait TmNat2Nat extends TmUnary
  trait TmNat2Bool extends TmUnary
  case object TmZero extends TmNat
  case class TmSucc(t: Tm) extends TmNat2Nat
  case class TmPred(t: Tm) extends TmNat2Nat
  case object TmTrue extends TmBool
  case object TmFalse extends TmBool
  case class TmIf(t1: Tm, t2: Tm, t3: Tm) extends TmTernary
  case class TmIsZero(t: Tm) extends TmNat2Bool
}
```

The hierarchy becomes multi-layered, where several intermediate datatypes are introduced and case classes/objects do not directly extend the root but an intermediate datatype. Traits in the second layer (TmNullary, TmUnary and TmTernary) classify terms
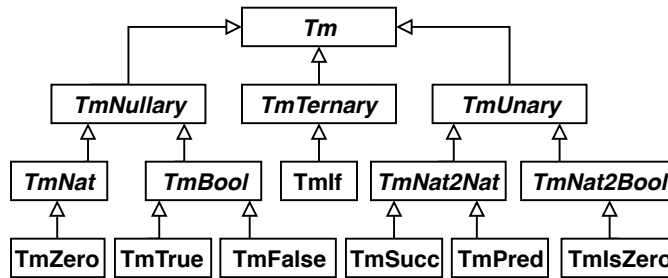
Figure 2: Hierarchical representation of Arith terms.

according to their arities. Based on arities, traits in the third layer (`TmNat`, `TmBool`, `TmNat2Nat`, `TmNat2Bool`) further classify terms according to their types. Concrete case classes/objects are in the fourth layer that extend a corresponding intermediate datatypes. For example, both `TmSucc` and `TmPred` extend `TmNat2Nat`.

### 3.2. Explicit Delegations

Now we illustrate the advantages of hierarchical datatypes. Suppose we would like to define a printer for Arith that prints out a term using an S-expression like format. For example, `TmIsZero(TmIf(TmFalse,TmTrue,TmPred(TmSucc(TmZero))))` is printed as `"(iszero (if false true (pred (succ 0))))"`. With terms being classified according to their arities, the printer can be modularized:

```scala
@visit(Tm) trait Print {
  type OTm = String
  def tmUnary(x: TmUnary, op: String) = "(" + op + " " + this(x.t) + ")"
  def tmSucc = tmUnary(_,"succ")
  def tmPred = tmUnary(_,"pred")
  def tmIsZero = tmUnary(_,"iszero")
  def tmZero = "0"
  def tmTrue = "true"
  def tmFalse = "false"
  def tmIf = x =>
    "(if " + this(x.t1) + " " + this(x.t2) + " " + this(x.t3) + ")"
}
```

Since all unary terms (`TmSucc`, `TmPred` and `TmIsZero`) are printed in the same way except for the operator, we define an auxiliary method `tmUnary`. Taking a `TmUnary` instance and an operator string as arguments, `tmUnary` puts the parentheses around the operator and the printed inner term of `TmUnary`. Then, `tmSucc`, `tmPred` and `tmIsZero` are implemented just by calling `tmUnary` with their respective instance and operator string.

### 3.3. Default Visitors

The previous example has shown how to enhance the modularity through explicit delegations. When subtypes share the same behavior with supertypes, the explicit delegations can be eliminated with the help of the generated default visitor. Currently, the Arith language presented allows ill-typed terms such as `TmPred(TmTrue)` to be constructed. To rule out these ill-typed terms, typechecking is needed. Some of the

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terms share typing rules: `TmTrue` and `TmFalse`; `TmSucc` and `TmPred`. With CASTOR's default visitor, we can avoid duplication of typing rules:

```
@adt trait Ty {
  case object TyNat
  case object TyBool
}
@default(Tm) trait Typeof {
  type OTm = Option[Ty]
  override def tmBool = _ => Some(TyBool)
  override def tmNat = _ => Some(TyNat)
  override def tmNat2Nat = x => this(x.t) match {
    case Some(TyNat) => Some(TyNat)
    case _ => None
  }
  override def tmNat2Bool = x => this(x.t) match {
    case Some(TyNat) => Some(TyBool)
    case _ => None
  }
  override def tmIf = x => (this(x.t1),this(x.t2),this(x.t3)) match {
    case (Some(TyBool),ty1,ty2) if ty1 == ty2 => this(x.t2)
    case _ => None
  }
  def tm = _ => None
}
```

Like `Tm`, `Ty` is a datatype for representing types, where `TyNat` and `TyBool` are two concrete types. A visitor `Typeof` is defined for typechecking terms. The output type of `Typeof` is `Option[Ty]`, indicating that if a term is well-typed, some type will be returned; otherwise a `None` will be returned. Except for `TmIf`, typing rules are defined on intermediate datatypes. For example, `tmNat2Nat` is overridden, which checks whether its inner term is of type `TyNat` and returns `TyNat` if so. `tmSucc` and `tmPred` are implicitly implemented by the inherited default visitor, whose definition is given below:

```
trait TmDefault extends TmVisit { _: TmV =>
  def tm: Tm => OTm
  def tmNullary = (x: TmNullary) => tm(x)
  def tmUnary = (x: TmUnary) => tm(x)
  def tmTernary = (x: TmTernary) => tm(x)
  def tmNat = (x: TmNat) => tmNullary(x)
  def tmBool = (x: TmBool) => tmNullary(x)
  def tmNat2Nat = (x: TmNat2Nat) => tmUnary(x)
  def tmNat2Bool = (x: TmNat2Bool) => tmUnary(x)
  def tmZero = tmNat(TmZero)
  def tmSucc = tmNat2Nat(_)
  def tmPred = tmNat2Nat(_)
  def tmTrue = tmBool(TmTrue)
  def tmFalse = tmBool(TmFalse)
  def tmIf = tmTernary(_)
  def tmIsZero = tmNat2Bool(_)
}
```

We can see that the default visitor extends the visitor interface with visit methods for intermediate datatypes and each visit method is implemented by delegating to its direct parent's visit method.

## 4. GADTs and Well-Typed EDSLs

In this section, we show the support for *generalized algebraic data types* (GADTs) [37] in Castor. GADTs allow not only datatypes to be parameterized but also well-formedness constraints to be expressed in constructors. GADTs are widely used for building well-typed domain-specific languages (EDSLs), which exploit the type system of the host language to typecheck the terms of the EDSL. Popular approaches to EDSLs like Finally Tagless [11] can provide an encoding of GADTs and provide modularity as well. However, the encoding employed by Finally Tagless is based on Church encodings. Unfortunately, this makes it hard to model several operations that require nested patterns or operations with dependencies. The interested reader is referred to Section 2 and 3 of the EVF paper [21] for a detailed discussion on the issue of Church encodings. We show that just as Finally Tagless encodings, modularity is supported; and like GADTs nested pattern matching and dependencies are easy to do as well.

### 4.1. GADTs and Well-Typed Terms

We have shown how to rule out ill-typed terms using a type-checking algorithm in Section 3.3. A better solution, however, is to prevent such terms from being constructed in the first place. This is possible through representing Arith terms using a GADT-style:

```scala
@family trait GArith {
  @adt trait Tm[A] {
    case object TmZero extends Tm[Int]
    case class TmSucc(t: Tm[Int]) extends Tm[Int]
    case class TmPred(t: Tm[Int]) extends Tm[Int]
    case object TmTrue extends Tm[Boolean]
    case object TmFalse extends Tm[Boolean]
    case class TmIf[A](t1: Tm[Boolean], t2: Tm[A], t3: Tm[A])
        extends Tm[A]
    case class TmIsZero(t: Tm[Int]) extends Tm[Boolean]
  }
}
```

`Tm` is now parameterized by a type parameter `A`. When declaring variants of `Tm`, the `extends` clause cannot be omitted anymore since Castor does not know how to instantiate `A`. Notice that `A` is instantiated differently as `Int` or `Boolean` for expressing well-formedness constraints. For example, `TmIsZero` requires its subterm `t` of type `Tm[Int]`. Consequently, one cannot supply a term of type `Tm[Boolean]` constructed from `TmTrue`, `TmFalse` or `TmIsZero` to `TmIsZero`. Therefore, ill-formed terms are statically rejected by the Scala type system:

```scala
TmIsZero(TmZero) // Accepted!
TmIsZero(TmTrue) // Rejected!
```

### 4.2. Well-Typed Big-Step Evaluator

As opposed to small-step semantics, big-step semantics immediately evaluates a valid term to a value. In the case of Arith, a term can either be evaluated to an integer or a boolean value. Without GADTs, implementing a big-step evaluator for Arith is tedious:

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```
     @family @adts(Tm) @ops(Eval1) trait EvalArith extends Arith {
       @adt trait Value {
         case class IntValue(v: Int)
         case class BoolValue(v: Boolean)
       }
       @visit(Tm) trait Eval {
         type OTm = Value
         def tmZero = IntValue(0)
         def tmSucc = x => this(x.t) match {
           case IntValue(n) => IntValue(n+1)
           case _ => throw NoRuleApplies
         }
         def tmPred = x => this(x.t) match {
           case IntValue(n) => IntValue(n-1)
           case _ => throw NoRuleApplies
         }
         def tmTrue = BoolValue(true)
         def tmFalse = BoolValue(false)
         def tmIf = x => this(x.t1) match {
           case BoolValue(true) => this(x.t2)
           case BoolValue(false) => this(x.t3)
           case _ => throw NoRuleApplies
         }
         def tmIsZero = x => this(x.t) match {
           case IntValue(0) => BoolValue(true)
           case IntValue(_) => BoolValue(false)
           case _ => throw NoRuleApplies
         }
       }
     }
```

EvalArith illustrates the operation extensibility of Castor, which does not introduce any new variants of Tm but a new visitor Eval on Tm. Auxiliary annotations @adts and @ops provide inherited datatypes and operations for Castor to generate the companion object. Such an implementation suffers from the so-called *tag* problem [11]: to accommodate different evaluation result types, an open datatype Value is defined for accommodating integers, booleans and many other evaluation result types that might be added in the future. The two variants IntValue and BoolValue are introduced for wrapping integers and boolean values, respectively. Pattern matching is used for unwrapping the evaluation results from inner terms. A defensive wildcard is needed for dealing with ill-typed terms. We can see that the tagging overhead is high.

Fortunately, we can avoid the tag problem with the help of Castor's GADTs. The extensible visitor encoding for GADTs is slightly different from the one presented in Section 2.7, which additionally take the type information carried by terms into account. For instance, the visitor interface generated for Tm[A] is listed below:

```
trait TmVisit { _: TmV =>
  type OTm[A]
  def apply[A](x: Tm[A]) = x.accept(this)
  def tmZero: OTm[Int]
  def tmSucc: TmSucc => OTm[Int]
  def tmPred: TmPred => OTm[Int]
  def tmTrue: OTm[Boolean]
  def tmFalse: OTm[Boolean]
```

```
      def tmIf[A]: TmIf[A] => OTm[A]
      def tmIsZero: TmIsZero => OTm[Boolean]
    }
```

Each visit method now returns a value of a higher-kinded type `OTm[A]`, where `A` is instantiated consistently with how it is instantiated in the `extends` clause. For example, `tmZero` is of type `OTm[Int]` while `tmTrue` is of type `OTm[Boolean]`. Then, a well-typed big-step evaluator can be made *tagless*:

```
@family @adts(Tm) trait EvalGArith extends GArith {
  @visit(Tm) trait Eval {
    type OTm[A] = A
    def tmZero = 0
    def tmSucc = x => this(x.t) + 1
    def tmPred = x => this(x.t) - 1
    def tmTrue = true
    def tmFalse = false
    def tmIf[A] = x => if (this(x.t1)) this(x.t2) else this(x.t3)
    def tmIsZero = x => this(x.t) == 0
  }
}
```

With the output type specified as `A`, the visit method returns a value of the type carried by the term. For example, visit methods `tmZero` and `tmTrue` return `Int` and `Boolean` values respectively. Moreover, this `Eval` implementation remains retroactive when terms of new types (such as `Tm[Float]`) are introduced.

Here are some terms that have different evaluation result types.

```
import EvalGArith._
eval(TmSucc(TmZero))   // 1
eval(TmIsZero(TmZero)) // true
```

*4.3. Well-Typed Small-Step Evaluator*

Well-typed big-step evaluators can be defined with Finally Tagless in an equally simple manner. What distinguishes Castor from Finally Tagless is the ability to define small-step evaluators in an easy way. The need for deep patterns and the dependency on a numeric value checker causes immediate trouble for Finally Tagless. Although workarounds may be possible for some of the issues, they are cumbersome and require significant amounts of boilerplate code [23]. In contrast, encoding small-step semantics in a GADT-style with Castor is unproblematic:

```
@family @adts(Tm) trait Eval1Arith extends GArith {
  def nv[A](t: Tm[A]): Boolean = t match {
    case TmZero => true
    case TmSucc(t1) => nv(t1)
    case _ => false
  }
  @default(Tm) trait Eval1 {
    type OTm[A] = Tm[A]
    def tm[A] = x => throw NoRuleApplies
    override def tmIf[A] = {
      case TmIf(TmTrue,t2,_) => t2
      case TmIf(TmFalse,_,t3) => t3
      case TmIf(t1,t2,t3) => TmIf(this(t1),t2,t3)
    }
```

```
1220    override def tmIsZero = {
          case TmIsZero(TmZero) => TmTrue
          case TmIsZero(TmSucc(t)) if nv(t) => TmFalse
          case TmIsZero(t) => TmIsZero(this(t))
        }
1225    ... // Other cases are the same as before
      }
    }
```

The instantiation of the output type guarantees that the small-step evaluator is *type-preserving*. That is, the type carried by a term remains the same after one step of evaluation. For example, calling `eval1` on `TmZero` will never return `TmTrue` no matter how `Eval1` is implemented. The actual definition of `Eval1` is almost the same as before except that `nv`, `tm` and `tmIf` become generic. Still, the ability to do nested pattern matching and to call `nv` in `Eval1` is preserved.

### 4.4. Extension: Higher-Order Abstract Syntax for Name Binding

A recurring problem in designing EDSLs is how to deal with binders. For example, in lambda calculus, operations involved with names like $\alpha$-equivalence and capture-avoiding substitution are non-trivial to define. Higher-order abstract syntax (HOAS) [38] avoids these problems through reusing the binding mechanisms provided by the host language. The following code shows how to extend ARITH with simply-typed lambda calculus modularly:

```
@family trait HOAS extends EvalGArith {
  @adt trait Tm[A] extends super.Tm[A] {
    case class TmVar[A](v: A) extends Tm[A]
    case class TmAbs[A,B](f: Tm[A] => Tm[B]) extends Tm[A => B]
1245    case class TmApp[A,B](t1: Tm[A => B], t2: Tm[A]) extends Tm[B]
  }
  @visit(Tm) trait Eval extends super.Eval {
    def tmVar[A] = _.v
    def tmAbs[A,B] = x => y => this(x.f(TmVar(y)))
1250    def tmApp[A,B] = x => this(x.t1)(this(x.t2))
  }
}
```

Three new forms of terms are introduced: lifters (`TmVar`), lambda abstractions (`TmAbs`) and applications (`TmApp`). Of particular interest is `TmAbs`, which constructs a term of type `Tm[A => B]` from a Scala lambda function `Tm[A] => Tm[B]` and thus is *higher-order*.

Correspondingly, `Eval` is extended with three new visit method implementations. `tmVar` simply extracts the value out of the lifter. `tmAbs` is trickier since it returns a value of type `A => B`. A lambda function is hence created, which takes `y` of type `A` and lifts it into `Tm[A]` using `TmVar`, then applies `x.f` to the lifted term for computing a `Tm[B]` and finally does a recursive call to evaluate `Tm[B]` into `B`. `tmApp` recursively evaluates `t1` and `t2`, which returns the value `A => B` and `A` respectively. Then it applies `A => B` to `A` for getting a value of `B`.

Here is an example that illustrates the use of `HOAS`:

```
import HOAS._
1265 eval(TmApp(TmAbs((t: Tm[Int]) => TmSucc(TmSucc(t))), TmZero)) // 2
```

We first create an abstraction term that applies successor twice to the argument `t` and then apply it to constant zero. Note that the type of `t` is explicitly specified because
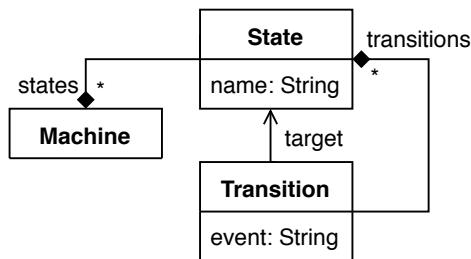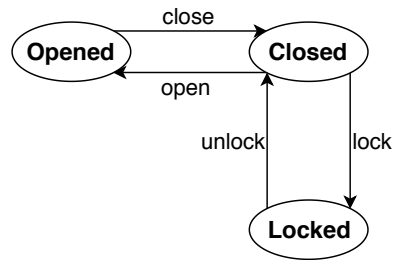
Figure 3: Class diagram of FSM.



Figure 4: A state machine for controlling a door.

Scala's type system is not powerful enough to infer the type of `TmAbs` without the type annotation.

## 5. Graphs and Imperative Visitors

Examples presented so far are all *functional* visitors (i.e. computation is done via returning values) on immutable trees. In fact, CASTOR also supports *imperative* visitors (i.e. computation is done via side effects) and data structures can be mutable graphs. Imperative computation is, in some cases, more efficient than the functional counterpart regarding time and memory. Compared to trees, graphs are a more general data structure that have many important applications. For instance, in the domain of compilers, abstract semantic graphs can be used for representing shared subexpressions, facilitating optimizations like common subexpression elimination. In this section, we show how to model graphs and imperative visitors with CASTOR.

### 5.1. The Difficulties in Modeling Graphs

Modeling graphs modularly is non-trivial in approaches such as Object Algebras [9]. Consider modeling a Finite State Machine (FSM) language. Figure 3 shows a UML class diagram for the FSM language. A `Machine` consists of some `States`. Each `State` has a name and a number of `Transitions`. A `Transition` is triggered by an `event`, taking one `State` to another. Concretely, Figure 4 shows a simple state machine for controlling a door, which has three states (opened, closed and locked) and four transitions (close, open, lock and unlock). From Figure 4 we can see that this state machine forms a *graph*, where we can go back and forth from one state to another along with the transitions.

*A Failed Attempt with Object Algebras.* Let us try to model the FSM language with Object Algebras. Describing the FSM language using a multi-sorted Object Algebra interface is unproblematic:

```scala
trait FSM[M,S,T] {
  def machine(states: List[S]): M
  def state(name: String, trans: List[T]): S
  def trans(event: String, target: S): T
}
```

where type parameters `M`, `S`, `T` represent different datatypes and factory methods capture their variants. However, constructing a graph using this representation is hard because

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Object Algebras support only immutable tree structures that are built *bottom up*. Here is a failed attempt on modeling the door state machine:

```scala
// Forward reference error!
def door[M,S,T](f: FSM[M,S,T]) = {
  val close: T = f.trans("close",closed)
  val open: T = f.trans("open",opened)
  val lock: T = f.trans("lock",locked)
  val unlock: T = f.trans("unlock",closed)
  val opened: S = f.state("opened", List(close))
  val closed: S = f.state("opened", List(open,lock))
  val locked: S = f.state("opened", List(unlock))
  f.machine(List(opened,closed,locked))
}
```

A *forward reference* error will always occur no matter how we arrange these statements. The reason is that there is no proper way to decouple the cyclic references between states and transitions.

## 5.2. *FSM in* Castor

Fortunately, modeling the FSM language using Castor is not a problem:

```scala
@family trait FSM {
  @adt trait M {
    val states = ListBuffer[S]()
    class Machine
  }
  @adt trait S {
    val trans = ListBuffer[T]()
    var name: String
    class State(var name: String)
  }
  @adt trait T {
    class Trans(val event: String, var target: S)
  }
  @visit(M,S,T) trait Print {
    type OM = String
    type OS = OM
    type OT = OM
    def machine = _.states.map{this(_)}.mkString("\n")
    def state = s => s.trans.map{this(_)}.mkString(s.name+":\n","\n","")
    def trans = t => t.event + " -> " + t.target.name
  }
  @visit(M,S,T) trait Step {
    type OM = String => Unit
    type OS = OM
    type OT = OM
    var res: S = null
    def machine = m => event => m.states.foreach{this(_)(event)}
    def state = s => event => s.trans.foreach{this(_)(event)}
    def trans = t => event => if (event == t.event) res = t.target
  }
}
```

The actual class hierarchies of the FSM language are slightly different from what Figure 3 shows. Each class in the UML diagram is defined inside an `@adt` trait for

allowing potential variant extensions. Fields are either declared as `var` or `val` for enabling/disabling mutability.

*Combined Visitors.* There are two visitors defined for the FSM language, namely `Print` and `Step`. Annotated as `@visit(M,S,T)`, both of them are *combined* visitors on transitions, states, and machines. Such a combined implementation is much more compact than defining three mutually dependent visitors with distinct names. `Print` instantiates the output types `OM`, `OS`, `OT` consistently as `String` and implements three visit methods `machine`, `state` and `trans` altogether. Concretely, methods `machine` and `state` map `Print` to the substructures and concatenate the results with a newline. For `trans`, we should not call `this` on the `target` state otherwise it will not terminate. Instead, we print out the `name` field on the `target` state only.

*Imperative Visitors.* The `Step` visitor captures a small-step execution semantics of FSM. Given an event, it goes through the structure for finding out the transition triggered by that event and returning the state that transition points to. Note that `Step` is also an *imperative* visitor, which instantiates the output types as `String => Unit` and updates the field `res` to the found target transition. If `res` is still `null` after traversal, then no such transition exists.

Now we are able to model the state machine that controls doors like this:

```
import FSM._
val door = new Machine
val opened = new State("Opened")
val closed = new State("Closed")
val locked = new State("Locked")
val open = new Trans("open",opened)
val close = new Trans("close",closed)
val lock = new Trans("lock",locked)
val unlock = new Trans("unlock",closed)
door.states += (opened,closed,locked)
opened.trans += close
closed.trans += (open,lock)
locked.trans += unlock
```

The graph is constructed in a conventional OOP style. Unlike Object Algebras, the structure is built *top down*. To decouple cyclic references, the declaration and initialization of the variables are separated. This is possible because unlike Object Algebras, variants in CASTOR are concrete classes provided with setters.

Calling `print(door)` produces the following output:

```
Opened:
close -> Closed
Closed:
open -> Opened
lock -> Locked
Locked:
unlock -> Closed
```

Some tests on `Step` are:

```
step(door)("open")
println(step.res.name) // "Opened"
step.res = null        // Reset to null
step(door)("close")
```

```
println(step.res.name) // "Closed"
```
Imperative visitors should be used more carefully. In the case of `Step`, its field `res`
needs to be reset to `null` afterwards. Otherwise, the result may be wrong next time we
call `step`.

### 5.3. Language Composition and Memoized Traversals

Consider unifying FSM and ARITH. The unification happens when a new kind of
transition called guarded transitions is introduced. A guarded transition additionally
contains a boolean term and is triggered not only by the event but also by the evaluation
result of that term. Combining FSM with the GADT version of ARITH is given below:

```
@family @adts(Tm,F,S) @ops(Eval)
trait GuardedFSM extends FSM with EvalArith {
  @adt trait T extends super[FSM].T {
    class GuardedTrans(event: String, target: State, val tm: Tm[Boolean])
      extends Trans(event, target)
  }
  @visit(M,S,T) trait Print extends super[FSM].Print {
    def guardedTrans = t => trans(t) + " when " + t.tm.toString
  }
  @visit(F,S,T) trait Step extends super[FSM].Step {
    def guardedTrans = t => event => if (eval(t.tm)) trans(t)(event)
  }
  @visit(S,T) trait Reachable {
    type OS = Unit
    type OT = Unit
    val reached = collection.mutable.Set[S]()
    def state = s =>
      if (!reached.contains(s)) {
        reached += s
        s.trans.foreach(this(_))
      }
    def trans = t => this(t.target)
    def guardedTrans = t => if (eval(t.tm)) this(t.target)
  }
}
```

Class `GuardedTrans` illustrates another form of hierarchical datatypes discussed in
Section 3, which extends an existing variant `Trans`. The additional field `tm` is of
type `Tm[Boolean]`, ensuring that the evaluation result is a boolean value. To handle
`GuardedTrans`, `Print` and `Step` are extended with an implementation of `guardedTrans`
method. Having `GuardedTrans` as a subtype of `Trans`, we are able to partially reuse the
semantics of `Trans` by calling the inherited `trans` method on a `GuardedTrans` instance.

*Memoized Traversals.* Naively traversing a graph might be inefficient because the same
object may be traversed multiple times. If not dealt with carefully, the traversal may
not even terminate. A more appropriate approach is to memoize the results of traversed
objects and fetch the cached result when an object is traversed again. `Reachable` is a
combined imperative visitor that finds out all reachable states for a given state. The
reachable states are collected in the `reached` field, which is initialized as an empty
mutable set. `Reachable` employs memoized depth-first search, which first checks
whether the state has already been traversed. If not, the state is added to `reached` and

$$
\begin{aligned}
\textit{Fam} \quad &::= \quad \texttt{@family @adts}(\overline{D}) \; \texttt{@ops}(\overline{V}) \; \texttt{trait } F \texttt{ extends } \overline{F}\{\overline{\textit{Adt}} \; \overline{\textit{Vis}}\} \\
\textit{Adt} \quad &::= \quad \texttt{@adt trait } D[\overline{X}] \texttt{ extends } \overline{\texttt{super}[F].D[\overline{X}]}\{\overline{\textit{Ctr}}\} \\
\textit{Ctr} \quad &::= \quad \texttt{class } C[\overline{X}] \texttt{ extends } \overline{(C[\overline{T}] \texttt{ with})? \, D[\overline{T}]} \\
&\quad | \quad \texttt{object } C \texttt{ extends } \overline{(C[\overline{T}] \texttt{ with})? \, D[\overline{T}]} \\
&\quad | \quad \texttt{trait } D[\overline{X}] \texttt{ extends } \overline{D[\overline{T}]} \\
\textit{Vis} \quad &::= \quad \texttt{@(default | visit)}(\overline{D}) \; \texttt{trait } V \texttt{ extends } \overline{\texttt{super}[F].V} \\
T \quad &::= \quad X \mid D[\overline{T}] \mid \texttt{Int} \mid T\texttt{=>}T
\end{aligned}
$$

Figure 5: Syntax.

the recursion goes to the states its transitions lead to. Similarly, memoization is also applicable to functional visitors by changing `reached` to a mutable map.

We can build a guarded door controller by changing the `import` statement and how `lock` is initialized:

```
val lock = new GuardedTrans("lock",locked,TmFalse)
```

Now, an opened door can no longer be locked because the guard evaluates to `false`:

```
reachable(open)
println(reachable.reached.size) // 2
```

By setting the expression to `TmTrue`, the door can be locked again:

```
lock.tm = TmTrue
reachable.clear // Reset to empty
reachable(open)
println(reachable.reached.size) // 3
```

## 6. Formalized Code Generation

In previous sections, we have shown code written with CASTOR and its corresponding generated code. In this section, we formally describe the valid Scala programs accepted by CASTOR and the transformation scheme.

### 6.1. Syntax

Figure 5 describes valid Scala programs accepted by CASTOR. Uppercase meta-variables range over capitalized names. $\overline{A}$ is written as a shorthand for a potentially empty sequence $A_1 \bullet \ldots \bullet A_n$, where $\bullet$ denotes `with`, comma or semicolon depending on the context. $(\ldots)$? denotes that $\ldots$ is optional. For brevity, we ignore the syntax that is irrelevant to the transformation, such as the `case` modifier, constructors, fields, and methods. These parts are kept unchanged after transformation.

### 6.2. Transformation

Figure 6 formalizes the transformation. We use semantic brackets ($\llbracket \cdot \rrbracket$) in defining the transformation rules and angle brackets (<>) for processing sequences. The transformation is given by pattern matching on the concrete syntax and is quite straightforward. One can see that processing the ARITH implementation in CASTOR (cf. Section 2.9) through Figure 6 will get back the extensible visitor implementation (cf. Section 2.7).

Here we briefly discuss some interesting cases. A `trait` is recognized as a *base case* if it extends nothing. Base cases have extra declarations such as `accept` declaration for

datatypes or `val` declaration for visitors. Variants declared using `class`, `trait` or `object` are treated differently. `object`s and `class`es have their corresponding visit methods in the visitor interface while visit methods for `trait`s only exist in the default visitor. The `extends` clause for `@adt` is used in inferring the `extends` clause for concrete visitors.

### 6.3. Implementation

Castor employs Scalameta [39] (version 1.8.0), a modern Scala meta-programming library, for analyzing and generating the code. The actual implementation closely follows the formalization. After parsing, the Scala source program is represented as an AST. We first check the validity of that AST with errors like annotating `@adt` not on a trait reported. We then generate code by analyzing the AST. Next, we build the AST with code injected. Finally, the AST is typechecked by the Scala compiler. During the process, Scala's quasiquotes are used, which allow us to analyze and rebuild the AST conveniently via the concrete syntax.

## 7. Case Study I: Types and Programming Languages

In this section, we present a case study on modularizing the interpreters in TAPL [22]. The Arith language and its variations are directly from or greatly inspired by the TAPL case study. TAPL are a good benchmark for examining Castor's capabilities of open pattern matching and modular dependencies. The reason is that core data structures of TAPL interpreters, types and terms, are modeled using algebraic datatypes; operations over types and terms are defined via pattern matching. There are a few operations that require nested patterns: small-step semantics, type equality, and subtyping relations. They all come with a default. The data structures and associated operations should be modular as new language features are introduced and combined. However, without proper support for modular pattern matching, the original implementation duplicates code for features that could be shared. With Castor and techniques shown in Section 2.9, we are able to refactor the non-modular implementation into a modular manner. Our evaluation shows that the refactored version significantly reduces the SLOC compared to a non-modular implementation found online. However, at the moment, improved modularity does come at some performance penalty.

### 7.1. Overview

An existing Scala implementation of TAPL[2] strictly follows the original OCaml version, which uses sealed case classes and pattern matching. The first ten languages (*arith*, *untyped*, *fulluntyped*, *tyarith*, *simplebool*, *fullsimple*, *fullerror*, *bot*, *rcdsubbot* and *fullsub*) are our candidates for refactoring. Each language implementation consists of 4 files: *parser*, *syntax*, *core* and *demo*. These languages cover various features including arithmetic, lambda calculus, records, fixpoints, error handling, subtyping, etc. Features are shared among these ten languages. However, such featuring sharing is achieved via duplicating code, causing problems like:

---

[2]`https://github.com/ilya-klyuchnikov/tapl-scala`

$[\![$ `@family @adts(`$\overline{D}$`)` `@ops(`$\overline{V}$`)` `trait` $F$ `extends` $\overline{F}\{\overline{Adt}\ \overline{Vis}\}$ $]\!] =$

  `trait` $F$ `extends` $\overline{F}\{[\![\overline{Adt}]\!]\ [\![\overline{Vis}]\!]\}$

  `object` $F$ `extends` $F\{$

    $\langle$`type` $D$V $= D$`Visit` $\mid D \in \overline{D} \cup \overline{Adt}\rangle$

    $\langle$`object` $v$ `extends` $V \mid V \in \overline{V} \cup \overline{Vis}\rangle$

  $\}$

$[\![$ `@adt` `trait` $D[\overline{X}]\{\overline{Ctr}\}$ $]\!] =$

  `type` $D$V `<:`$D$`Visit`

  `trait` $D[\overline{X}]\{$`def` `accept(v:`$D$`V):` `v.O`$D[\overline{X}]\}$

  $[\![\overline{Ctr}]\!]$

  `trait` $D$`Visit{` `_:`$D$`V` `=>`

    `type` O$D[\overline{X}]$

    `def` `apply[`$\overline{X}$`](x:`$D[\overline{X}]$`)` `=` `x.accept(``this``)`

    $[\![\overline{Ctr}]\!]_{visit}$

  $\}$

  `trait` $D$`Default` `extends` $D$`Visit{` `_:`$D$`V` `=>`

    `def` $d[\overline{X}]:D[\overline{X}]$ `=>` O$D[\overline{X}]$

    $[\![\overline{Ctr}]\!]_{default}$

  $\}$

$[\![$ `@adt` `trait` $D$ `extends` $\overline{\text{super}[F].D}\{\overline{Ctr}\}$ $]\!] =$

  `type` $D$V `<:`$D$`Visit`

  $[\![\overline{Ctr}]\!]$

  `trait` $D$`Visit` `extends` $\overline{\text{super}[F].D\text{Visit}}\{$ `_:`$D$`V` `=>`$[\![\overline{Ctr}]\!]_{visit}\}$

  `trait` $D$`Default` `extends` $D$`Visit` `with` $\overline{\text{super}[F].D\text{Default}}\{$`_:`$D$`V` `=>` $[\![\overline{Ctr}]\!]_{default}\}$

$[\![$`class` $C[\overline{X}]$ `...`$]\!] =$ `class` $C[\overline{X}]$ `...`$\{$ `override` `def` `accept(v:`$D$`V)` `=` `v.`$c$`(``this``)`$\}$

$[\![$`object` $C$ `...`$]\!] =$ `object` $C$ `...`$\{$ `override` `def` `accept(v:`$D$`V)` `=` `v.`$c\}$

$[\![Ctr]\!] = Ctr$

$[\![$`class` $C[\overline{X}]$ `extends` $(\ldots\text{with})? D[\overline{T}]$ $]\!]_{visit} =$ `def` $c[\overline{X}]:C$ `=>` O$D[\overline{T}]$

$[\![$`object` $C$ `extends` $(\ldots$ `with`$)? D[\overline{T}]$ $]\!]_{visit} =$ `def` $c:$ O$D[\overline{T}]$

$[\![Ctr]\!]_{visit} = \varnothing$

$[\![$`class` $C_1[\overline{X}]$ `extends` $C_2[\overline{T}]\ldots]\!]_{default} =$ `def` $c_1[\overline{X}]$`=` `x` `=>` $c_2($`x`$)$

$[\![$`object` $C_1$ `extends` $C_2[\overline{T}]\ldots]\!]_{default} =$ `def` $c_1 = c_2(C_1)$

$[\![$`trait` $D_1[\overline{X}]$ `extends` $D_2[\overline{T}]\ldots]\!]_{default} =$ `def` $d_1 = ($`x:`$D_1[\overline{X}])$ `=>` $d_2($`x`$)$

$[\![$`@(`$\text{default} \mid \text{visit})(\overline{D})$ `trait` $V]\!] =$

  `trait` $V$ `extends` $\overline{D(\text{Default} \mid \text{Visit})}\{$ `_:`$\overline{D\text{V}}$`=>`$\ldots\}$

  `val` $v : V$

$[\![$`@(`$\text{default} \mid \text{visit})(\overline{D})$ `trait` $V$ `extends` $\overline{\text{super}[F].V}]\!] =$

  `trait` $V$ `extends` $\overline{D(\text{Default} \mid \text{Visit})}$ `with` $\overline{\text{super}[F].V}\{$ `_:`$\overline{D\text{V}}$`=>`$\ldots\}$

$[\![\overline{X}]\!] = \langle[\![X]\!] \mid X \in \overline{X}\rangle$
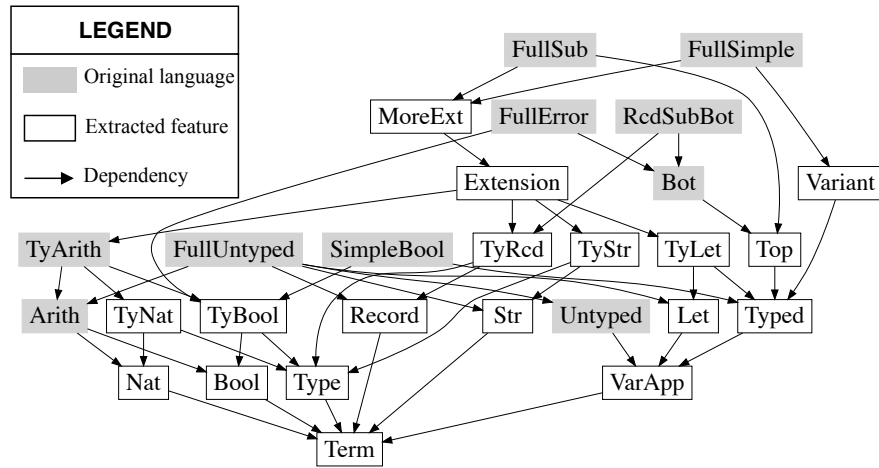
Figure 6: Transformation.

Figure 7: Simplified language/feature dependency graph.

- **Inconsistent definitions.** Lambdas are printed as `"lambda"` in all languages except for *untyped*, where lambdas are printed as `"\"`.

- **Feature leaks.** Features introduced in the latter part of the book (e.g., System F) leak to previous language implementations such as *fullsimple*.

Our refactoring focuses on *syntax* and *core* where datatypes and associated operations are defined. Figure 7 gives a simplified high-level overview of the refactored implementation. The candidate languages are represented as gray boxes whereas extracted features/sub-languages are represented as white boxes. From Figure 7 we can see that the interactions between languages (revealed by the arrows) are quite intense. Take ARITH for example, it is a sublanguage for *tyarith*, *fulluntyped*, *fullerror*, *fullsimple* and *fullsub*. Unfortunately, without proper modularization techniques, the original implementation repeats the definition of *arith* at least five times. In the refactored implementation written with CASTOR, however, *arith* is defined only once and modularly reused in other places.

## 7.2. Evaluation

We evaluate CASTOR by answering the following questions:

- **Q1.** Is CASTOR effective in reducing SLOC?

- **Q2.** How does CASTOR compare to EVF?

- **Q3.** How much performance penalty does CASTOR incur?

*Q1.* Table 2 reports the SLOC comparison results. With all the features/sublanguages extracted, implementing a candidate language with CASTOR is merely done by composing features/sublanguages. Therefore, the more features/sublanguages the candidate

Table 2: SLOC evaluation of TAPL interpreters

| Extracted | Castor | EVF | Language | Castor | EVF | Scala |
|-----------|--------|-----|----------|--------|-----|-------|
| bool | 71 | 98 | arith | 31 | 33 | 106 |
| extension | 24 | 34 | untyped | 40 | 46 | 124 |
| str | 42 | 55 | fulluntyped | 18 | 47 | 256 |
| let | 48 | 47 | tyarith | 22 | 26 | 157 |
| moreext | 112 | 106 | simplebool | 24 | 38 | 212 |
| nat | 85 | 103 | fullsimple | 24 | 83 | 619 |
| record | 117 | 198 | fullerror | 68 | 105 | 396 |
| top | 79 | 86 | bot | 40 | 61 | 190 |
| typed | 82 | 138 | rcdsubbot | 30 | 39 | 257 |
| varapp | 40 | 65 | fullsub | 57 | 116 | 618 |
| variant | 136 | 161 | | | | |
| misc | 212 | 172 | **Total** | **1402** | **1857** | **2935** |

language uses, the more code Castor reduces. Compared to the non-modular Scala implementation, for a simple language like *arith*, the reduction rate[3] is 71%; for a feature-rich language like *fullsimple*, the reduction rate can be up to 96%. Overall, Castor reduces over *half* of the total SLOC with respect to the non-modular version.

*Q2.* Table 2 also compares Castor with EVF [21]. Castor reduces over 400 SLOC compared to EVF. As we have shown in Section 2, the reduction comes from the native support for pattern matching, generated dependency declarations, etc. More importantly, the instantiation burden for EVF is heavy if there are a lot of visitors and the dependencies are complex. In contrast, Castor completely removes the instantiation burden by generating companion objects automatically.

*Q3.* To measure the performance, we randomly generate 10,000 terms for each language and calculate the average evaluation time for 10 runs. The ScalaMeter[4] microbenchmark framework is used for performance measurements. The benchmark programs are compiled using Scala 2.12.7, JDK version 1.8.0_211 and are executed on a MacBook Pro with 2.3 GHz quad-core Intel Core i5 processor with 8 GB memory. Figure 8 compares the execution time in milliseconds. From the figure we can see that Castor implementations have a 1.35x (*arith*) to 3.92x (*fullsub*) slowdown with respect to the corresponding non-modular Scala implementations. The more features a modular implementation combines, the more significant the slowdown is. Figure 9 further compares the performance of the Scala Arith implementations discussed in Section 2. Obviously, modular implementations are slower than non-modular implementations. With the underlying optimizations, the implementation based on sealed case classes is faster than the implementation based on conventional visitors.

We believe that the performance penalty is mainly caused by method dispatching. A modular implementation typically has a complex inheritance hierarchy. Dispatching on

---

[3]Reduction rate = $\dfrac{\textbf{Scala SLOC} - \textsc{Castor SLOC}}{\textbf{Scala SLOC}} \times 100\%$
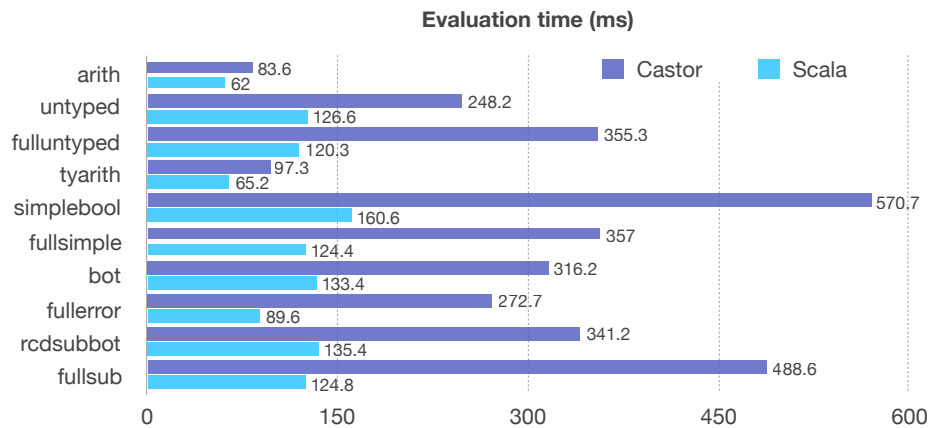
[4]http://scalameter.github.io

**Evaluation time (ms)**



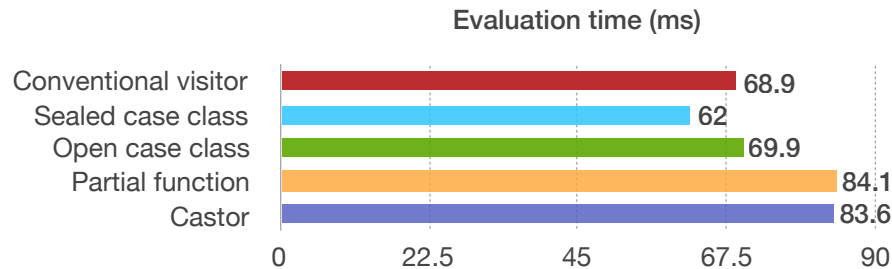Figure 8: Performance evaluation of TAPL interpreters.

**Evaluation time (ms)**



Figure 9: Performance evaluation of ARITH.

a case needs to go across that hierarchy. Thus, the more complex the hierarchy is, the worse the performance is. Another source of performance penalty might be the use of functions instead of normal methods in visitors. Of course, more rigorous benchmarks need to be conducted to verify our guesses. One possible way to boost the performance is to turn TAPL interpreters into compilers via staging using the LMS framework [40]. This is currently not possible because LMS and Scalameta are incompatible in terms of the Scala compiler versions.

*Threats to Validity.* There are two major threats to the validity of our evaluation. The first threat is that measuring conciseness by counting SLOC may not be fair especially when different languages are used. We mitigate this threat by making the code style and the maximum character-per-line consistent for each implementation. The second threat is the representativeness of the TAPL interpreters. They are small languages for teaching purposes. It might still be questionable whether CASTOR scale to model larger languages that are actually used in practice. Nevertheless, TAPL interpreters have already covered a lot of core features that are available in mainstream languages.
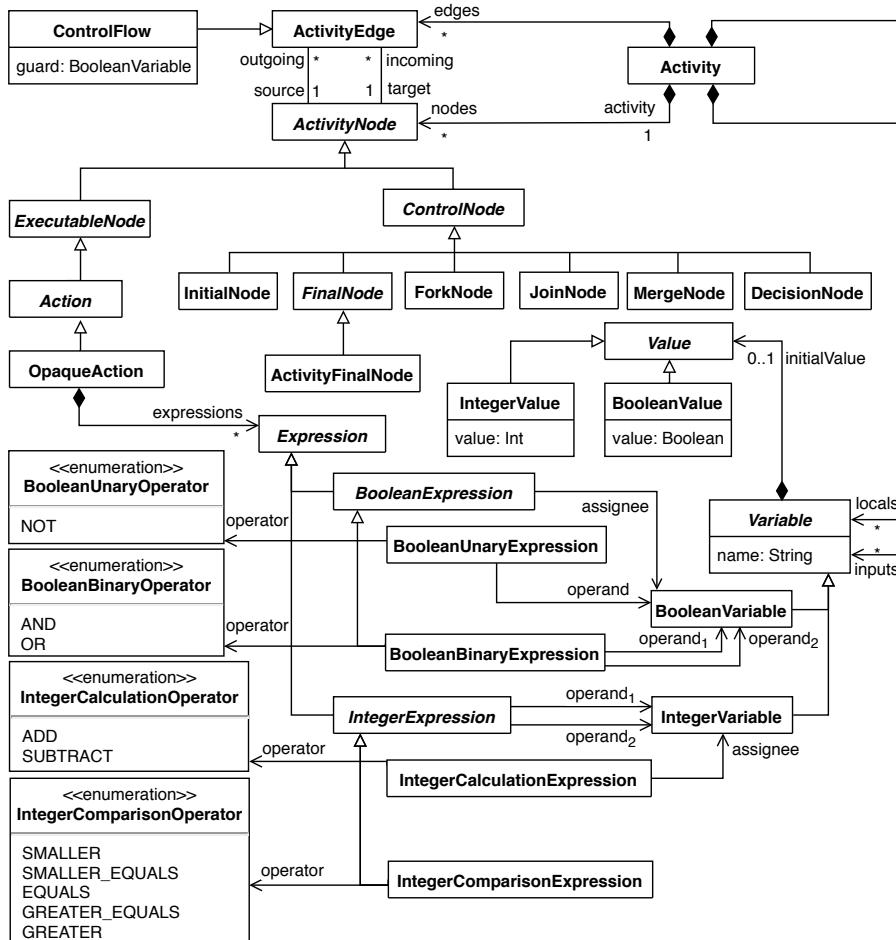
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Figure 10: Metamodel of UML Activity Diagrams (an excerpt adapted after the TTC'15 document [41]).

## 8. Case Study II: UML Activity Diagrams

In Section 7, we have evaluated the functional aspects of CASTOR. In this section, we evaluate the imperative aspects of CASTOR. To do so, we conduct another case study on a subset of the UML activity diagrams, which can be seen as a richer language than the FSM language discussed in Section 5. This case study examines hierarchical datatypes, imperative visitors and graphs.

### 8.1. Overview

An execution model of UML activity diagrams has been proposed as one of the challenges of the Transformation Tool Contest (TTC'15).

*Metamodel.* Figure 10 shows the metamodel of UML activity diagrams, where ***Name*** denotes abstract classes and **Name** denotes concrete classes. An `Activity` object

represents an instance of a UML activity diagram, which contains a sequence of
`ActivityNodes` and `ActivityEdges`. `ExecutableNode` and `ControlNode` are two inter-
mediate types of `ActivityNode` for classifying nodes that perform actions or control
the flow. There are several concrete nodes. `InitialNode` and `ActivityFinalNode` are
the start/end of activity diagrams; `DecisionNode` and `MergeNode` are the start/end of
alternative branches; `ForkNode` and `JoinNode` are the start/end of concurrent branches.
On the other hand, `OpaqueAction` sequentially executes a sequence of `Expressions`.
`ActivityNodes` are connected by `ActivityEdges`. Similar to `GuardedTrans` discussed
in Section 5.3, a `ControlFlow` is a specialized `ActivityEdge`, which is guarded by the
current `BooleanValue` stored in a `BooleanVariable`. `Expressions` are also organized in
a hierarchical way according to their types (`Boolean` or `Integer`) and the number of
operands (`Unary` or `Binary`).

*Goal and Challenges.* The goal is to extend this simplified metamodel of UML activity
diagrams with the dynamic execution semantics. The semantics is defined by performing
transitions on activity nodes step by step using an imperative style. Several *runtime
concepts* need to be introduced. Adding these runtime concepts poses two modularity
challenges: *operation extensions* and *field extensions*. One example of an operation
extension is `execute`, which is added to the `Expression` hierarchy for executing the
calculation. One example of a field extension is a mutable boolean value `running`, which
is added to `ActivityNode` for distinguishing triggered nodes from others.

*Reference Implementation.* The reference implementation[5] is written in Java with
EMF [42]. The metamodel is described in Ecore from which Java interfaces are gen-
erated. Then semantics is encoded by defining classes that implement those interfaces
using the INTERPRETER pattern [18]. The reference is non-modular because the INTER-
PRETER pattern facilitates adding new classes but lacks the ability to add new operations.
Therefore, the reference implementation has to anticipate the operations on the meta-
model. Moreover, consistent with what Figure 10 shows, operators were modeled as
enumerations and recognized using `switch-case` clauses in Java, which are closed for
extensions.

*Refactored Implementation.* Our refactoring only focuses on the metamodel and the
semantics parts. Since the original implementation is written in Java, we first port it into
Scala and then refactor it using CASTOR. Figure 11 gives an overview of the refactored
implementation, which consists of four CASTOR components. Concretely, we make the
following changes to the ported implementation for increasing modularity:

1. **Separate metamodel and operations.** With CASTOR, we do not need to fore-
   see the operations on the metamodel since operations can be modularly added
   afterwards. Thus, the refactored implementation separates the metamodel and
   operations upon it respectively in **\*Model** and **\*Lang**.
2. **Expression language as an independently reusable component.** Values, vari-
   ables and expressions are essentially a sublanguage independent of the UML

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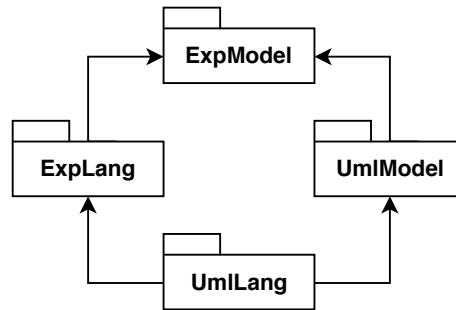[5]`https://github.com/moliz/moliz.ttc2015`

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Figure 11: Refactored implementation.

activity diagrams. Instead of defining the expression sublanguage together with UML activity diagrams within a single `@family` component, we extract its metamodel into **ExpModel** and its semantics into **ExpLang** and let **UmlModel** and **UmlLang** extend them respectively. This allows the expression sublanguage to be reused or extended individually.

3. **Overridden methods as visitors.** Methods that are overridden in the subclasses are rewritten as visitors, such as `isReady` and `fire` on `ActivityNode` and `execute` on `Expression`. Since only a few cases of `isReady` and `fire` are overridden whereas every case of `execute` is overridden, we use the default visitor (annotated as `@default`) for the former and the ordinary visitor (annotated as `@visit`) for the latter. For non-overridden methods, we move them out of a class and use an explicit argument to capture `this`.

4. **Operators as open datatypes.** Operators are refactored as `@adt` hierarchies and their semantics are given by visitors for enabling extensions. This allows new kinds of operators such as multiplication to be added later.

*8.2. Evaluation*

We evaluate CASTOR by answering the following questions:

- **Q1.** Does the refactoring preserve the behavior of the ported implementation?

- **Q2.** Can CASTOR solve the modularity challenges?

- **Q3.** How does the refactoring affect the SLOC?

- **Q4.** Is the performance overhead reasonable?

*Q1.* To make sure that our refactoring does not affect the correctness of the implementation, we ran the test suite provided by the TTC'15 document. The test suite contains 6 small activity diagrams where all kinds of `ActivityNodes` and `Expressions` are covered. The refactored implementation passes all the tests in the test suite. This gives us some confidence that the refactored implementation preserves the behavior of the ported implementation.

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Table 3: Performance evaluation in milliseconds.

| Name | Description | INTERPRETER | CASTOR |
|---|---|---|---|
| test$_1$ | 1000 sequential actions | 22.1 | 56.6 |
| test$_2$ | 100 parallel branches each with 10 actions | 20.7 | 39.8 |
| test$_3$ | Similar to test$_2$ with a variable increased | 22.8 | 39.9 |

*Q2.* For the operation extension challenge, the answer is yes. Operations are added by defining new visitors, which are fully modular. However, CASTOR does not address the field extension challenge very well. With the current version of CASTOR, we cannot extend existing classes with additional fields while keeping their names. The workaround is to introduce subclasses of different names. For example, if we want to extend `ActivityNode` with a field called `running`, we have to define a new class called `RuntimeActivityNode` that extends `ActivityNode` with `running`. The drawback is that `RuntimeActivityNode` and `ActivityNode` coexist and all existing operations need to be modified for handling `RuntimeActivityNode`. It is possible to have an alternative design for CASTOR, which does not introduce a new name while accomplishing field extensions in CASTOR. However, this brings some other complications. Such alternative design is discussed in Section 9.2.

*Q3.* The SLOC of the ported version and the refactored version are 489 and 411 respectively. Surprisingly, the refactoring brings extra modularity while reducing the SLOC. One reason is that in the ported version, methods are first declared in traits and then implemented in classes while the refactored version needs no prior declarations. Another reason is that by properly using CASTOR's default visitors and combined visitors, some definitions can be shortened. For example, `Execute` in the refactored version is a combined visitor for `Expression` and 4 operators.

*Q4.* We reuse the test suite provided by the TTC'15 document, which includes 3 large activity diagrams for measuring the performance. Table 3 gives a simple description for each test case and the average execution time for 10 runs (measured in milliseconds) for the two implementations. The benchmark is executed using the same machine specified in Section 7. The CASTOR's implementation is around 2 to 3 times slower than the non-modular ported implementation. These results are similar to the results we get in Section 7 and further confirm that CASTOR's modular implementation introduces an acceptable performance penalty.

*Threats to Validity.* One threat to the validity of the evaluation is that the test suite is very small and might not be able to find out bugs that are introduced by refactoring. Also, directly comparing a CASTOR's implementation with respect to the reference implementation may be unfair since different programming languages are used. To exclude such language-wise factor on evaluation, we compared to the ported Scala implementation. As our focus is on the semantics part, irrelevant code like parsing is ignored.

**9. Limitations and Design Options**

In this section, we first discuss the limitations of CASTOR, which affect some of the design decisions we made that lead CASTOR to its current form. We then discuss other design options and compromises.

*9.1. Limitations*

CASTOR has some limitations due to the use of metaprogramming and the restrictions from the current Scalameta library:

- **Unnecessary annotations.** With the current version of Scalameta, we are not able to get information from annotated parents. If parents' information were accessible, the inherited datatypes and visitors could be analyzed and `@adts` and `@ops` annotations could be eliminated.

- **Boilerplate for nested composition.** Lacking of parents' information also disallows automatically composing nested members. Assuming that automatic nested composition is available, `Arith` can be simplified as:

```
@family trait Arith extends Nat with Bool {
  @adt trait Tm { ... }
  @visit(Tm) trait Eval1 { ... }
}
```

where the `extends` clause is expressed only once in the family level and `extends` clauses for nested members such as `super[Nat].Tm with super[Bool].Tm` are inferred.

- **Imprecise error messages.** As CASTOR modifies the annotated programs, what the compiler reports are errors on the modified program rather than the original program. Reasoning about the error messages becomes harder as they are mispositioned and require some understanding of the generated code.

*9.2. Design Options*

*Nested Patterns.* There is an alternative way of writing nested patterns. For example, `tmIf` can be rewritten in the following way:

```
override def tmIf = x => x.t1 match {
  case TmTrue => x.t2
  case TmFalse => x.t3
  case t1 => TmIf(this(t1),x.t2,x.t3)
}
```

Instead of directly pattern matching on an `TmIf` object, we capture it first using a variable x and then explicitly `match` on its subterm t1. For the case of `tmIf`, this alternative implementation is arguably less intuitive than the version we presented in Section 2.9. Nevertheless, this approach comes in handy when: 1) the object being matched contains a lot of fields and most of them are not interesting in nested patterns; 2) there are a lot of `case` clauses for nested patterns and repeating the top-level pattern in each `case` clause becomes tedious.

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<span>1730</span> *Specialized Visitors.* Programming with visitors can be simplified using specialized visitors. The default visitors generated by CASTOR (annotated as `@default`) are an instance. In fact, there are more such specialized visitors. For example, visitors can be combined with *visitor combinators* [43]; boilerplate for querying and transforming data structures can be eliminated by *traversal templates* [21]. Essentially, these specialized <span>1735</span> visitors can also be generated by CASTOR. Currently, only default visitors are generated because 1) in our experience they are most frequently used; 2) generating all other infrequently used specialized visitors increases the time of code generation and the size of generated code. Ideally, specialized visitors should be generated by need. Limited by current Scalameta, this is impossible for the moment.

<span>1740</span> *Refinable Variants.* As our visitor encoding shows, the key to extensibility is capturing concrete types with bounded type members for allowing future refinements. The same idea can also be applied to variants, where the visitor method signature refers to a type member instead of a class name. By doing this, we are able to extend that class with additional fields seamlessly by covariantly refining the type member to the new <span>1745</span> class. An application of refinable variants would be guarded transitions discussed in Section 5.3:

```scala
class Trans(event: String, to: State, var tm: Tm[Boolean] = TmTrue)
  extends super.Trans(event, to)
```

Instead of adding a new variant called `GuardedTrans`, we refine the existing `Trans`. The <span>1750</span> benefit is that existing visitors that do not concern about the additional parameter `tm` can be unchanged. In contrast, for the case of `GuardedTrans`, we have to update all existing visitors with an implementation of `guardedTrans`. However, the downside of supporting refinable variants in CASTOR is that it brings more book-keeping burden on variants for the user. We consider the price to pay is higher than the benefit it brings.

<span>1755</span> ## 10. Related Work

*Object-Oriented Pattern Matching.* There are many attempts to bring notions similar to pattern matching into OOP. Multimethods [3, 44] allow a series of methods of the same signature to co-exist. The dispatching for these methods additionally takes the runtime type of arguments into consideration so that the most specific method is <span>1760</span> selected. Pattern matching on multiple arguments can be simulated with multimethods. However, it is unclear how to do deep patterns with multimethods. Also, multimethods significantly complicate the type system. As we have discussed in Section 2, case classes in Scala [31] provide an interesting blend between algebraic datatypes and class hierarchies. Sealed case classes are very much like classical algebraic datatypes, and <span>1765</span> facilitate exhaustiveness checking at the cost of a closed (non-extensible) set of variants. Open case classes support pattern matching for class hierarchies, which can modularly add new variants. However no exhaustiveness checking is possible for open case classes. Besides case classes, extractors [32] are another alternative pattern matching mechanism in Scala. An extractor is a companion `object` with a user-defined `unapply` method that <span>1770</span> specifies how to tear down that object. Unlike case classes whose `unapply` method is automated and hidden, extractors are flexible, independent of classes but verbose. There are also proposals to extend mainstream languages with pattern matching such as

Java. JMatch [45] extends Java with pattern matching using modal abstraction. JMatch methods additionally have backward modes that can compute the arguments from a given result, serving as patterns. Follow-up work [46] extends JMatch with exhaustiveness and totality checking on patterns in the presence of subtyping and inheritance. However, it requires a non-trivial language design with the help of an SMT solver. More recent OO languages like Newspeak [47] and Grace [48] are designed with first-class pattern matching, where patterns are objects and can easily be combined. To the best of our knowledge, none of these approaches fully meet the desirable properties summarized in Section 2.1.

*Modular Church-Encoded Interpreters.* Solutions to the Expression Problem based on Church encodings can also be used for developing modular interpreters. Well-known techniques are Finally Tagless [11], Object Algebras [9] and Polymorphic Embedding [12]. However, these techniques do not support pattern matching or dependencies, making it hard to define operations like small-step semantics discussed in Section 2. Although Kiselyov [23] shows that operations requiring nested patterns can be rewritten as context-sensitive operations, the operations become much more convoluted. Typical workarounds on dependent operations are defining the operation together with the dependencies or using advanced features like intersection types and a merge operator [49, 50]. In contrast, Castor allows us to implement operations that need nested patterns and/or with dependencies in a simple, modular way.

*Polymorphic Variants.* OCaml supports polymorphic variants [51]. Unlike traditional variants, polymorphic variant constructors are defined individually and are not tied to a particular datatype. Garrigue [52] presents a solution to the Expression Problem using polymorphic variants. To correctly deal with recursive calls, open recursion and an explicit fixed-point operator must be used properly. Otherwise, the recursion may go to the original function rather than the extended one. This causes additional work for the programmer, especially when the operation has complex dependencies. In contrast, Castor handles open recursion easily through OO dynamic dispatching, reducing the burden of programmers significantly.

*Open Datatypes and Open Functions.* To solve the Expression Problem, Löh and Hinze [53] propose to extend Haskell with open datatypes and open functions. Different from classic closed datatypes and closed functions, the open counterparts decentralize the definition of datatypes and functions and there is a mechanism that reassembles the pieces into a complete definition. To avoid unanticipated captures caused by classic *first-fit* pattern matching, a *best-fit* scheme is proposed, which rearranges patterns according to their specificness rather than the order (e.g. wildcards are least specific). However open datatypes and open functions are not supported in standard Haskell and more importantly, they do not support separate compilation: all source files of variants belonging to the same datatype must be available for code generation.

*Data Types à la Carte (DTC).* DTC [54] encodes composable datatypes using existing features of Haskell. The idea is to express extensible datatypes as a fixpoint of co-products of functors. While it is possible to define operations that have dependencies

or require nested pattern matching with DTC, the encoding becomes complicated and needs significant machinery. There is some follow-up work that tries to equip DTC with additional power. Bahr and Hvitved [55] extend DTC with GADTs [37] and automatically generates boilerplate using Template Haskell [56]. Oliveira et al. [57] use list-of-functors instead of co-products to better simulate OOP features including subtyping, inheritance, and overriding.

*Language Workbenches.* To reduce the engineering effort involved in software language development, language workbenches [58, 59] have been proposed. Modularity is an important concern in language workbenches for allowing existing language components to be reused in developing new languages [60]. Traditionally most of the work on language workbenches has focused on *syntactic modularity* approaches. More *semantic modularity* aspects such as separate compilation and modular typechecking are not well addressed. However, more recent work on language workbenches has started to incorporate semantic modularity techniques. We compare our work next, to the language workbenches that employ semantic modularization techniques. With Neverlang [61], users do not directly program with visitors. Instead, they have to use a DSL and learn specific concepts such as slice and roles. MontiCore [62] generates the visitor infrastructure from its grammar specification. To address the extensibility issue, MontiCore overrides the `accept` method and uses casts for choosing the right visitor for extended variants, thus is not type-safe. Also, MontiCore supports imperative style visitors only. Alex [63] also provides a form of semantic modularity based on the *Revisitor* pattern [64], which can be viewed as a combination of Object Algebras and Walkabout [65]. By moving the dispatching method from the class hierarchy to the visitor interface, the *Revisitor* pattern can work for legacy class hierarchies that do not anticipate the usage of visitors. However, the dispatching method generated by Alex is implemented using casts and has to be modified whenever new variants are added, thus is neither modular nor type-safe. Castor fully supports semantic modularity and allows users to do the development using their familiar language with a few annotations. For the moment, Castor still lacks much of the functionality for various other aspects of language implementations that are covered by language workbenches. Nevertheless, the modularization techniques employed by Castor could be useful in the context of language workbenches to improve reuse and type-safety of language components, in the same way that visitors are used in Neverlang and Revisitors are used in Alex.

## 11. Conclusion and Future Work

In this paper, we have presented Castor, a Scala framework for programming with extensible, generative visitors using simple annotations. Visitors written with Castor are type-safe, concise, exhaustive, extensible and composable. Moreover, both functional and imperative style visitors are supported. We have shown how to use Castor in designing a better pattern matching mechanism in an OOP context, developing modular well-typed EDSLs, doing extensible programming on graphs, etc. The effectiveness of Castor is validated by our case studies on TAPL interpreters and UML activity diagrams. While Castor is practical and serves the purpose of programming with visitors, there are important drawbacks on such a meta-programming, library-based

approach: error reporting is imprecise; the syntax and typing of Scala cannot be changed to enforce certain restrictions. In future work, we would like to design a language with a better surface syntax that supports first-class visitors. Another direction of future work is to grow Castor into a language workbench by additionally supporting syntax and associated tools development.

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