Why Nominal-Typing Matters in Object-Oriented Programming

Moez A. AbdelGawad
College of Mathematics and Econometrics, Hunan University
Changsha 410082, Hunan, P.R. China
Informatics Research Institute, SRTA-City
New Borg ElArab, Alexandria, Egypt
moez@cs.rice.edu

November 1, 2016

Abstract

The statements ‘inheritance is not subtyping’ and ‘mainstream OO languages unnecessarily place restrictions over inheritance’ have rippled as mantras through the PL research community for years. Many mainstream OO developers and OO language designers, however, do not accept these statements. In nominally-typed OO languages that these developers and language designers are dearly familiar with, inheritance simply is subtyping; and they believe OO type inheritance is an inherently nominal notion, not a structural one.

Nominally-typed OO languages, such as Java, C#, C++, and Scala, are among the most used programming languages today. However, the value of nominal typing to mainstream OO developers, as a means for designing robust OO software, seems to be in wait for full appreciation among PL researchers—thereby perpetuating an unnecessary schism between many OO developers and language designers and many OO PL researchers, with each side discounting, if not even disregarding, the views of the other.

In this essay we strengthen and complement earlier efforts to demonstrate the semantic value of nominal typing by presenting a technical comparison between nominal OO type systems and structural OO type systems. Recently, a domain-theoretic model of nominally-typed OOP was compared to well-known models of structurally-typed OOP. Combined, these comparisons provide both a clear technical account and a deep mathematical account of the relation between nominal and structural OO type systems that have not been presented before, and they help demonstrate the key value of nominal typing and nominal subtyping to OO developers and language designers.

We believe a clearer understanding of the key semantic advantage of pure nominal OO typing over pure structural OO typing can help remedy the existing schism. We believe future foundational OO PL research, to further its relevance to mainstream OOP, should be based less on structural models of OOP and more on nominal ones instead.

1 Introduction

In 1990, Cook et al. shocked the programming languages (PL) research community by declaring that, in object-oriented programming, ‘inheritance is not subtyping,’ meaning there is no one-to-one correspondence between type inheritance and subtyping in OO programming languages, further adding that mainstream OO languages unnecessarily ’place re-
strictions over inheritance. Over the years, these statements rippled, as mantras, through the PL research community.

To this day, however, many mainstream OO developers and OO language designers cannot digest or accept not identifying type inheritance with subtyping. Simply, the statement of Cook et al. is not true in nominally-typed OO languages that these developers and language designers are dearly familiar with. Further, they see that the so-called “restriction” of type inheritance in nominally-typed OO languages is strongly justified, or, more so, that a structural view of inheritance is in fact an unjustified redefinition of type inheritance, which they view as an inherently nominal notion.

Nominally-typed OO languages are among the top most-used programming languages today. Examples of nominally-typed OO languages include many industrial-strength mainstream OO programming languages such as Java [44], C# [1], C++ [2], and Scala [61]. Nominally-typed OO languages have remained among the top most-used programming languages for over a decade [14, 5]. And, even by the most conservative measures, these languages are expected to remain among the top most-used OO programming languages in the near future, if not the far one, too.

In spite of this, the value of nominal typing and nominal subtyping to mainstream OO developers, as a means for designing robust OO software that can be readily understood and maintained, as well as the value of properties of OO type systems that depend on nominality to them (such as the identification of type inheritance with subtyping), seem to be not yet fully appreciated among OO PL researchers. This has led to a continuing tension and schism between two large and significant communities: many mainstream OO developers and OO language designers, on one side, and many OO PL researchers, on the other side, with each of both sides discounting, and even disregarding, the views and opinions of the other.

In nominally-typed (a.k.a., nominatively-typed) OO languages, objects and their types are nominal, meaning that objects and their types carry class names information as part of the meaning of objects and of the meaning of their types. Class names—and interface names and trait names in OO languages that support these notions—are used as type names in nominally-typed OO languages. Class—and interface and trait—behavioral contracts, typically written informally in code documentation comments, are specifications of the behavioral design intentions of OO software developers. In nominally-typed OOP, a reference to a class (or interface or trait) name is invariably considered a reference to the associated contract too. Given this association of type names to corresponding behavioral contracts, nominal typing allows associating types of objects with (formal or informal) behavioral contracts.

By using type names in their code, OO developers using nominally-typed OO languages have a simple way to refer to the corresponding contracts—referring to them as richer specifications of object state and behavior that can be checked statically and that can be used during runtime. This readily access to richer object specifications—which cannot be expressed in a natural way using non-nominal (a.k.a., structural) record types that, by definition, include no class names information—makes nominally typed OO languages closer to being semantically typed languages than structurally typed OO languages are.

The first mathematical models of OOP to gain widespread recognition among programming languages (PL) researchers were developed while OOP was making its first steps into mainstream computer programming. (See Section 2.) These early models were structural models of OOP. As the developers of these models themselves (e.g., Cardelli) explained, this was due to influence from functional programming research extant at that time. These models of OOP, thus, reflected a view of OOP that does not include class names information.

Being structural, objects were viewed in these models simply as being records (of functions). Object types, in accordance, were viewed as record types, where the type of an object only specifies the structure of the object, meaning that object types carry information only on the names of the members of objects (i.e., fields and methods) and, inductively, on the (structural) types of those members. Examples of structurally-typed OO languages include lesser-known languages such as O’Caml [48], Modula-3 [27],
In pure structurally-typed OO languages, class names information (also called nominal information) is not used as part of the identity of objects and their types, neither during static type checking nor at runtime. Accordingly, nominal information is missing in structural mathematical models of OOP.

The main practical advantage of structural typing over nominal typing in OO languages seems to be their “flexibility,” i.e., the ability in a structurally-typed OO language to have supertypes get defined “after the fact” (i.e., after their subtypes are already defined). In light of mainstream OO developers of statically-typed OO languages not adopting structural typing, the “inflexibility” of nominally-typed OO languages seems not to be enough justification for wider use of structural typing, particularly in light of the advantages of nominal typing we discuss in this essay.

We attempt thus in this essay to further close the gap that exists between programming language researchers who maintain a structurally-typed view of OOP (and who believe in conclusions based on this view, such as inheritance and subtyping not being in one-to-one correspondence) and mainstream OO software developers and OO language designers who maintain a nominally-typed view of OO software (and who, accordingly, reject conclusions based on the structural view) by giving a precise technical account of the relation between nominal and structural OO type systems. The essay complements the recent mathematical comparison of a nominal domain-theoretic model of OOP to structural domain-theoretic models of OOP.

This essay is structured as follows. First, in Section 2 we give some details on the history of modeling OOP, particularly details relevant to realizing differences between nominal typing and structural typing and to the development of nominal and structural models of OOP.

Given that structural typing, more or less, is understood well among PL researchers, in Section 3 we directly demonstrate the value of behavioral contracts and nominal typing in mainstream nominally-typed OO languages using a comparison, followed by a discussion of the comparison. In Section 3.1 we first discuss, in some detail, the value of contracts and the value of identifying inheritance with subtyping in mainstream OO software design. Then, using code examples, in Section 3.2 and Section 3.3 we compare nominally-typed OO type systems and structurally-typed ones to more vividly illustrate the main technical differences between them. We then conclude in Section 3.4 by discussing the nominal and structural views of type names and of recursive-types, and the importance of recursive types in mainstream OOP.

We conclude the essay by summarizing our findings, and making some final remarks, in Section 4.

2 Related Work

Even though object-oriented programming emerged in the 1960s, and got mature and well-established in mainstream software development in the 1980s, the differences between nominally-typed and structurally-typed OO programming languages started getting discussed by PL researchers only in the 1990s [53, 65, 68]. In spite of an early hint by Cardelli (see below), the value of investigating nominal typing and nominal subtyping and their value to OO developers was not appreciated much however—that is, until about a decade later, around the year 2000.

In the eighties, while mainstream OOP was in its early days, Cardelli built the first denotational model of OOP [24, 25]. Cardelli’s work was pioneering, and naturally, given the research on modeling functional programming extant at that time (which Cardelli heavily referred to and relied on), the model Cardelli constructed was a structural denotational model of OOP.

A discussion of statically-typed versus dynamically-typed OO languages (including the non-well-defined so-called “duck-typing”), and the merits and demerits of each, is beyond the scope of this essay. The interested reader should check [56]. In this essay, we focus on nominal and structural statically-typed OO languages.

2 Quite significantly, Cardelli in fact also hinted at looking for investigating nominal typing [26, p.2]. Sadly, Cardelli’s hint went largely ignored for years, and structural typing was rather assumed superior to nominal typing instead, particularly after
In the late eighties/early nineties, Cook and his colleagues worked to improve on Cardelli’s model. Unlike Cardelli, Cook et al. emphasized in their work the importance of self-references in OOP, at the value level and at the type level. Their research led them to break the identification of type/interface inheritance with subtyping [22, 35, 34].

In 1994, Bruce and others presented a discussion of the problem of binary methods in OOP [22] (a “binary method” is a method that takes a parameter or more of the same type as the class the method is declared in). Later, Bruce and Simons promoted the structural view of OOP and conclusions based on it in a number of publications (e.g., [23] and [65]), in spite of the disagreement between these conclusions and the fundamental intuitions of a significant portion of mainstream OO developers and language designers [28].

Under the pressure of this disagreement, some PL researchers then started in the late nineties/early 2000s stressing the significance of the differences between nominally-typed OOP and structurally-typed OOP, and they started acknowledging the practical value of nominal typing and nominal subtyping [65]. Accordingly some attempts were made to develop OO languages with complex type systems that are both nominally- and structurally-typed [8, 10, 12, 54, 55]. However, in the eyes of mainstream OO developers, these “hybrid” languages have more complex type systems than those of languages that are either simply purely nominally-typed or purely structurally-typed. This more complexity typically results in lesser productivity for developers who attempt to use both of the typing approaches in their software (see also discussion at the end of Section 3.4).

As to operational models of OOP, Abadi and Cardelli were the first to present such a model [6]. The publication of Cook et al.’s and Bruce et al.’s work as we later discuss.

3A discussion of Cardelli’s model and of Cook’s model and a comparison of NOOP, a nominal domain-theoretic model of OOP [8, 10], versus the structural models of Cardelli and Cook is presented in [11, 13].

4See our later discussion of ‘false/spurious binary methods’—methods that are mistakenly identified by structural OO type systems as being binary methods but their semantics are not those of true binary methods.

In 2000s stressing the significance of the differences between nominally-typed OOP and structurally-typed OOP, and they started acknowledging the practical value of nominal typing and nominal subtyping [65]. Accordingly some attempts were made to develop OO languages with complex type systems that are both nominally- and structurally-typed [8, 10, 12, 54, 55]. However, in the eyes of mainstream OO developers, these “hybrid” languages have more complex type systems than those of languages that are either simply purely nominally-typed or purely structurally-typed. This more complexity typically results in lesser productivity for developers who attempt to use both of the typing approaches in their software (see also discussion at the end of Section 3.4).

As to operational models of OOP, Abadi and Cardelli were the first to present such a model [6]. The publication of Cook et al.’s and Bruce et al.’s work as we later discuss.

3A discussion of Cardelli’s model and of Cook’s model and a comparison of NOOP, a nominal domain-theoretic model of OOP [8, 10], versus the structural models of Cardelli and Cook is presented in [11, 13].

4See our later discussion of ‘false/spurious binary methods’—methods that are mistakenly identified by structural OO type systems as being binary methods but their semantics are not those of true binary methods.

7Again, their model had a structural view of OOP. However, operational models of nominally-typed OOP got later developed. In their seminal work, Igarashi, Pierce, and Wadler presented Featherweight Java (FJ) [45] as an operational model of a nominally-typed OO language. Even though FJ is not the first operational model of nominally-typed OOP (see [50], [50] and [50], for example), FJ is the most widely known operational model of (a tiny core subset of) a nominally-typed mainstream OO language, namely Java. The development of FJ and other operational models of nominally-typed OOP motivated the construction of NOOP as the first domain-theoretic model of nominally-typed OOP [8, 10].

Given the different basis for deriving data structuring in functional programming (based on standard branches of mathematics) and in object-oriented programming (based on biology and taxonomy), Featherweight Java [45] offers a very clear operational semantics for a tiny nominally-typed OO language. It is worth mentioning that domain-theoretic models of nominally-typed OO languages, as more foundational models that have fewer assumptions than operational ones, provide a denotational justification for the inclusion of nominal information in FJ. The inclusion of nominal information in NOOP was crucial for proving the identification of inheritance with subtyping in nominally-typed OOP [8, 10]. In FJ [45], the identification of inheritance with subtyping was taken as an assumption rather than being proven as a consequence of nominality. Also, domain-theoretic models such as NOOP allows discussing issues of OOP such as type names, ‘self-types’ and binary methods on a more foundational level than provided by operational models of OOP such as FJ. The more abstract description of denotational models results in a conceptually clearer understanding of the programming notions described as well as the relations between them.

(It is also worth mentioning that NOOP was developed, partially, in response to the technical challenge Pierce presented in his LICS’03 lecture [42] in which Pierce looked for the precise relation between structural and nominal OO type systems, notably after the development of FJ was concluded, implying that the question about the relation remained an open question after the development of FJ. As to their purpose, it is customary that denotational models and operational ones play complementary roles, where denotational models are usually of more interest to programming language designers, while operational ones are usually of more interest to programming language implementers.)

6Which is a fact that seemingly is nowadays forgotten by some PL researchers but that Cardelli explicitly mentions in [24, 25].
some PL researchers have also expressed dissatisfaction with assuming that the views of programming based on researching functional programming (including a view that assumes structural typing) may apply, without qualifications, to object-oriented programming. In addition to Pierce and other earlier and later researchers pointing out the importance of distinguishing between nominal typing and structural typing, MacQueen [51], for example, also noted many mismatches between Standard ML (a popular functional programming language [59]) and class-based OO languages such as Java and C++. Later, Cook [33] also pointed out differences between objects of OOP and abstract data types (ADTs) that are common in functional programming.

These research results run in a similar vein as ours since they somewhat also point to some mismatches between the theory and practice of programming languages—theory being more mathematics-based, functional, and structurally-typed, and practice being more biology/taxonomy-based, object-oriented, and nominally-typed.

3 Nominally-Typed OOP versus Structurally-Typed OOP

In this section we first informally and less-technically, discuss the importance of contracts, and of nominal typing and nominal subtyping to mainstream OO developers in Section 3.1—briefly discussing DbC (Design by Contract) in the process, then we discuss how LSP (Liskov’s Substitution Principle) expresses the importance of preserving contracts upon inheritance. In Section 3.2 and Section 3.3, we then present code examples that illustrate how nominally-typed OOP and structurally-typed OOP compare to each other from a technical point of view, and illustrate how structural typing and structural subtyping sometimes force the breaking of contracts. In the comparison we discuss two key problems with structural OO type systems, namely, ‘spurious subsumption,’ and its converse, ‘missing subsumption.’

We then conclude our demonstration of the value of nominal typing by discussing, in some depth, the nominal and structural views of type names and of recursive-types, and the importance of recursive types in mainstream OOP in Section 3.4.

The discussions and comparisons in this section demonstrate that nominal typing in nominally-typed OO programming languages causes typing and subtyping in these languages to be closer to semantic typing and subtyping, respectively, because of the association of nominal information with class contracts. This closeness to semantic typing, the simplicity of the resulting software design mental model, and the importance of recursive types to mainstream OO developers and OO language designers help explain the practical value of nominal typing to mainstream OO developers and OO language designers.

3.1 Contracts, Nominality and The Liskov Substitution Principle (LSP)

Contracts are widely-used notions in mainstream OO software development. A contract in an OO program is similar to a contract in the real world: It specifies what an object expects of client objects and what client objects can expect of it. Members of an object—i.e., its fields and methods—and properties of these members form the object’s interface with the outside world; the buttons on the front of a television set, for example, are the interface between us and the electrical wiring on the other side of the TV’s plastic casing. One presses the “power” button and he or she are promised this will turn the television on and off. In its most common form, an interface is a group of related methods together with a contract giving promises on the behavior of these methods. Similarly, a class contract is an agreement that instances of the class will expose (present as their public interface, or API) certain methods, certain properties, and certain behaviors.

---

A technical overview of main OO typing notions that explains some of the technical jargon used in this essay is presented in [9].
Contract Examples  Examples of contracts in OO software are plenty. Examples familiar to most Java developers, for example, include the contract of the `Comparable` interface promising its clients a total ordering on its elements and requiring that classes that implement the interface adhere to this promise, and the contract of class `Object` promising that the `equals()` method and the `hashCode()` method are in agreement and requiring subclasses that override one of the two methods to override the other method accordingly.

Also in Java, class `JComponent` contains a default implementation of all of the methods in the `Accessible` interface, but `JComponent` is not actually declared to implement the interface, because the contract associated with `Accessible` is not satisfied by the default implementation provided in `JComponent`. This example stresses the association of inherited contracts with superclass names. In mainstream OO software, if a class extends another class or implements an interface it is declaring that it inherits the contract associated with the superclass or superinterface and will maintain it. Likewise, if a class does not maintain the contract associated with another class or implements an interface it is declaring that it inherits the contract associated with the superclass or superinterface and will maintain it. We discuss this point further in Section 3.1.1.

Other examples of contracts may also include a class that implements tree layout algorithms. The contract of such a class may require the input graph to be a tree, and may promise as result, if the input is a tree, to produce a layout that has no overlapping nodes, edges or labels.

In general, contracts, whether written formally or informally, usually contain the following pieces of information: side effects, preconditions, postconditions, invariants, and, sometimes, even performance guarantees. In Java, class contracts, as a set of requirements and promises, are usually stated in Javadoc comments. Requirements of a contract are simply any conditions on the use of the class, for example: conditions on argument values, conditions on the order of execution of methods, conditions on execution in a multi-threaded or parallel environment.

Two further, rather artificial, examples for contracts, that we will expound on below to show the differences between nominal typing and structural typing, are the promise that an animal can play with any another animal, and the promise that a (mathematical) set contains no repeated elements. In particular, we use these two examples to show how structural subtyping can lead to breaking contracts associated with classes/interfaces/traits.

From the presented examples, it is easy to see that a contract is made of two parts: requirements upon the caller (“the client”) made by the class (“the provider”) and promises made by the class to the caller. If the caller fulfills the requirements, then the service provider will deny its service. If any postcondition or invariant is violated, it uncovers a problem on the service provider side [46]. As such, the benefits and obligations of clients and providers, along with their relative chronological order, can be summarized as in Table 1.

| Provider                  | Client                  |
|---------------------------|-------------------------|
| (2) Input guaranteed to   | (4) Output guaranteed   |
| comply to preconditions    | comply to postconditions|
| (no need to check input)   | (no need to check output)|
| (3) Satisfy postconditions | (1) Satisfy preconditions|

Table 1: Design By Contract (DbC): Benefits and Obligations [Source: [46]]

Further, according to proponents of ‘Design By Contract’ (DbC), classes of a software system communicate with one another on the basis of precisely defined benefits and obligations [57, 58]. If preconditions are not obeyed by the client of the class method, the service provider will deny its service. If any postcondition or invariant is violated, it uncovers a problem on the service provider side [46]. As such, the benefits and obligations of clients and providers, along with their relative chronological order, can be summarized as in Table 1.

Nominal-Typed OOP  Moving on from DbC to the design of mainstream OO type systems, OO languages should ideally include behavioral contracts in object types. Motivated by DbC, contracts are used
by mainstream OO developers for constructing robust, reliable, reusable and maintainable OO software, since contracts promise specified properties of objects. For example, in his widely-known book titled ‘Effective Java’ [16, 17], Joshua Bloch reflects on the use of contracts in mainstream OOP and asserts the value of contracts to OO software design by writing that, ‘No class is an island. Instances of one class are frequently passed to another. Many classes depend on the objects passed to them obeying the contracts associated with their superclasses ... once you’ve violated the contract, you simply don’t know how other objects will behave when confronted with your object.’

In practice however, the inclusion of behavioral contracts in object types is too much to ask of a type checker (because of the general problem of not being able to statically check contracts, since behavioral contracts are remarkably expressive). The solution OO language designers choose is to go with an approximation. The association of class names with contracts, and OO type systems respecting nominal information in typing and subtyping decisions, allows a nominally-typed OO type system to be a tractable approximation of DbC; hence, OO language designers of many mainstream OO languages use nominal typing. Nominally-typed OO languages typically do not require the enforcement of requirements and promises of contracts; requirements and promises are rather assumed to hold, thereby encouraging but not requiring developers to enforce the contracts. To accurately reflect how contracts are used in nominally-typed OOP, Table 1 can as such be modified into Table 2.

### Table 2: Contracts in Nominally-Typed OOP: Benefits and Obligations

| Benefit                  | Obligation                     |
|--------------------------|--------------------------------|
| (4) Output assumed to    | (1) Satisfy contract promises  |
| comply to contract       | (no need to check output)     |
| promises (no need to     |                                |
| act requirements        |                                |
| (2) Input assumed to     | (3) Satisfy contract promises  |
| comply to contract       | (no need to check input)       |
| requirements (no need to|
| act promises            |                                |
|                         |                                |

3.1.1 Inheritance, Subsumption and Contract Preservation

As to the inheritance of contracts in mainstream OOP, implementing an interface, for example, allows a class in an OO program to become more formal about the behavior it promises to provide. Interfaces form a contract between a class and the outside world. In a statically-typed language the tractable component of the contract is enforced at build time by the compiler. In Java, for example, if a class claims to implement an interface, all methods defined by that interface must appear in its source code before the class will successfully compile, and during runtime it is assumed the promises given by the interface are maintained by the class. The same happens if a class claims to extend another class, or if an interface claims to extend another interface. This inheritance of requirements and promises is sometimes referred to as interface inheritance, contract inheritance, or type inheritance.

While using inheritance, it may be necessary to make changes to a superclass contract. Some changes to a specification/contract will break the caller, and some will not. For determining if a change will break a caller, professional OO developers use the memorable phrase “require no more, promise no less”: if the new specification does not require more from the caller than before, and if it does not promise to de-

---

8 According to [17], “Programmers employ inheritance for a number of different purposes: to provide subtyping, to reuse code, to allow subclasses to customise superclasses’ behaviour, or just to categorise objects”. Inheritance as only being ‘a method by which classes share implementations’ (i.e., it being a ‘code sharing/code reuse’ technique), is a very limited notion of inheritance that, unfortunately, is still entertained by some OO PL researchers. Code sharing is only a part of the fuller picture of OO inheritance, and is only a means towards the higher goal of classes sharing their contracts (and even their architectures [37, 11]), not just their code. Inheritance as ‘contract sharing’ is the notion of inheritance that we are generally interested in and discuss in this essay.
liver less than before, then the new specification is compatible with the old, and will not break the caller.

Bloch [16, 17], hinting at the conventional wisdom among mainstream OO developers that identifies type inheritance with subtyping, proceeds to conclude, based on his earlier observations about contracts, that

‘inheritance [of contracts] is appropriate only in circumstances where the subclass really is a subtype of the superclass.’

As such, Bloch concludes that

‘it is the responsibility of any subclass overriding the methods of a superclass to obey their general contracts; failure to do so will prevent other classes that depend on the contracts from functioning properly in conjunction with the subclass.’

The requirement that subclasses maintain the contracts of their superclasses is expressed among professional OO developers by stating that well-designed OO software should obey the Liskov substitution principle (LSP) [49, 50]. According to Bloch [16, 17],

‘The LSP says that any important property of a type should also hold for its subtypes, so that any method written for the type should work equally well on its subtypes [49, 50].’

As such, as demonstrated by Bloch, it is common knowledge among professional mainstream OO developers that subsumption (as expressed by the LSP) and the identification of inheritance with subsumption (i.e., subtyping between object types) are an integral part of the mental model of object-oriented programming. Whenever these principles are violated, a program becomes more difficult to understand and to maintain. (For example, after his discussion of contracts Bloch then gives examples demonstrating problems, in the Java libraries which Bloch himself coauthored, that resulted from violating these principles [16, 17].)

Based on the discussion of contracts and inheritance, two clear OO design principles among professional mainstream OO developers are:

1. Whenever the contract of a class/interface/trait is obeyed by an inheriting class (i.e., whenever we have type inheritance) we should have subsumption between corresponding class types (i.e., we should have subtyping), and, conversely,

2. Whenever we have subsumption between two class types (i.e., whenever we have subtyping) the contracts (of the superclass type) should be obeyed by the subclass type (i.e., we should have type inheritance).

Given the importance of the LSP (as expressing the preservation of contracts upon inheritance) to mainstream OO developers, and given that contracts are typically specifications of object behavior, it is easy to conclude that basing typing on contracts so as to make typing and subtyping closer to behavioral typing and behavioral subtyping (sometimes also called ‘semantic typing’ and ‘semantic subtyping’) is a desirable property of an OO language.

To further illustrate the importance of identifying inheritance with subtyping to OO software developers, in the following two sections we present code examples that point out two problems with structural subtyping that do not exist in nominally-typed OOP.

The first problem is what is sometimes called the problem of ‘spurious subsumption’ ([63, p.253]), and the second is the problem of inheritance not implying subtyping (which we call ‘missing subsumption’), i.e., that inheritance between two classes does not imply subsumption between the two corresponding class types (the converse of the spurious subsumption problem).[10]

[9]The LSP is the third of the five OO design principles (the L in ‘SOLID’) mainstream OO developers follow to design robust OO software. In the jargon of OO developers, OO code “smells” (in particular, it has a ‘refused bequest’) if some class in the code does not obey LSP, i.e., if a derived class— that is, a subclass—in the code breaks the contract of one of its base classes—that is, of one of its superclasses. The LSP thus expresses that class contracts are preserved by inheriting classes.

[10]The code examples can be skipped by a reader familiar with these two problems.
In the spurious subsumption problem, we have two classes whose instances do not maintain the same contract but are considered subtypes according to structural subtyping rules, demonstrating an example of structural subtyping breaking LSP. In the missing subsumption problem, we have two classes whose instances do maintain the same behavioral contract but that are not considered subtypes in a structural type system, due to structural type systems rebinding self-types upon inheritance, demonstrating an example of structural subtyping thus breaking the identification between inheritance and subtyping.

Further, due to pure structural OO type systems always requiring the rebinding of self-types upon inheritance, we also point out a so-far-unknown problem with pure structural subtyping that we call the problem of ‘spurious binary methods’.

### 3.2 Spurious Subsumption

In structurally-typed OOP, subtyping does not imply inheritance, that is, we may have subtyping between types corresponding to two classes (instances of one can be used as that of the other) but not have an inheritance relation between these two classes. To illustrate, let us assume the following definitions for class `Set` and class `MultiSet` (where the contract of class `Set` disallows repetition of elements of a `Set`, in agreement with the mathematical definition of sets, whereas the contract of class `MultiSet` allows repetition of elements of a `MultiSet`, in agreement with the mathematical definition of multisets, sometimes also called bags),

```java
class Set {
    Boolean equals(Object s) { ... }
    Void insert(Object o) { ... }
    Void remove(Object o) { ... }
    Boolean isMember(Object o) { ... }
}

class MultiSet {
    Boolean equals(Object ms) { ... }
    Void insert(Object o) { ... }
    Void remove(Object o) { ... }
    Boolean isMember(Object o) { ... }
}
```

We note in the code for class `Set` and class `MultiSet` that the two classes support precisely the same set of four operations on their instances having the same signatures for these four operations. The different contracts associated with the two classes, specifying that the semantics and run-time behavior of their instances should agree with the corresponding mathematical notions, are reflected only in the different class names of the two classes but not in the structure of the two classes.

Given that nominally-typed OOP respects class names (and thus the associated class contracts) while structurally-typed OOP ignores them, we have the final assignment in

```java
MultiSet m = new MultiSet();
m.insert(2);
m.insert(2);
Set s = m; // Allow assignment?
```

correctly disallowed in nominally-typed OOP, but is wrongly allowed in structurally-typed OOP. The assignment is not allowed in nominally-typed OOP because class `MultiSet` does not inherit from class `Set`, while it is allowed in structurally-typed OOP because of matching signatures of all operations supported by the two classes. The assignment should not be allowed because, if allowed (as demonstrated in the code above), it will allow repetition of a set’s elements in the value bound to variable `s` by the assignment (given that it is an instance of `MultiSet`). Variable `s`, by its declaration, is assumed to be a `Set` (with no repeated elements), and the assignment, if allowed, will thus break the contract of class `Set` associated with variable `s`.

The problem of spurious subsumption is similar to the problem of accidentally mistaking values of a datatype for those of another datatype (think of using floats for modeling euros and dollars then mistaking euros for dollars or mistaking floats for either). Similarly, OO software developers think of an object in the context of its class hierarchy and of the contracts associated with its class members. A key precept of nominally-typed OOP is that class contracts are inherited along with class members and should be maintained by instances of inheriting subclasses. Spurious subsumption in structurally-typed OOP al-
allows for unintended breaking of this rule, since a structural type checker fails to reject a program that uses an object of one type where a behaviorally different, but structurally compatible, type is expected.

3.3 Inheritance Is Not Subtyping

Another problem with structural subtyping is the converse of the spurious subsumption problem. In structurally-typed OO languages, structural subtyping does not require subtyping between types of classes that are in the inheritance relation (and thus have inherited contracts), i.e., inheritance does not imply subtyping. In combination with subtyping not implying inheritance (i.e., spurious subsumption), structural subtyping thus totally separates the notions of inheritance and subtyping, based on its non-nominal view of inheritance which ignores the inheritance of class contracts associated with class names.

To illustrate inheritance not implying subtyping in structurally-typed OOP, assume the following definitions for class Animal and class Cat:

```java
class Animal {
    void move(Point to) { ... } // more generic animal behavior,
    void eat(Food some) { ... } // ... from class Animal
    void breathe() { ... } // ... }

class Cat extends Animal {
    Animal mate(Animal a) { ... } // behavior specific to cats
    // generic animal behavior inherited // from class Animal

    // but, do Cats...
    Cat mate(Cat c) { ... } // OR do they...
    Animal mate(Animal a) { ... } // ???
}
```

Structurally-typed and nominally-typed OOP disagree on the signature of method `mate()` in class Cat. Structurally-typed OOP assumes that `mate()` is a binary method (See [22], where binary methods were recognized as problematic and multiple approaches were suggested for dealing with them. We discuss them more technically in Section 3.4), and requires the method to have the “more natural” signature `Cat mate(Cat c)`, at the expense of making Cats (i.e., instances of class Cat) not be Animals (i.e., instances of class Animal) when they (quite naturally) should be one.

Nominally-typed OOP, on the other hand, does not assume the `mate()` method in class Animal to be a binary method. It thus keeps using the same signature for the method upon its inheritance by class Cat. In nominally-typed OOP, thus, Cats are indeed Animals, meaning that nominally-typed mainstream OOP does identify inheritance with subtyping. Given how nominally-typed OOP and structurally-typed OOP differ on whether inheritance implies subtyping,

11 For example, as mentioned earlier, interface Comparable in Java, consisting of the single abstract method `int compareTo(Object o)`, has a public contract asserting that `compareTo` defines a total ordering on instances of any class inheriting from Comparable, and that clients of Comparable can thus depend on this property. An arbitrary class with a method `int compareTo(Object o)`, however, generally-speaking does not necessarily obey this contract. In structurally-subtyped OO languages, instances of such a class can be bound, by spurious subsumption, to variables of type Comparable (similar to allowing the binding of the instance first bound to variable a to variable s in the Set/MultiSet example above). This is in spite of the fact that when a developer asserts that a class C implements Comparable, he or she is asserting that `compareTo()` defines a total ordering on class C, and the author of Comparable conversely asserting that if a class C does not implement the Comparable interface, instances of C cannot be bound to variables of type Comparable, since the `compareTo` method of C may unintentionally or intentionally not define a total ordering on instances of C.

12 That is, in structurally-typed OO languages the structural type corresponding to class Cat is not a subtype of the structural type corresponding to class Animal (because of the contravariance of types of method arguments), unless some unintuitive structural notion, like ‘matching’ [23] (which expresses the similarity of recursive structure) between class Cat and class Animal, but which did not gain traction or support in mainstream OOP), is added to the language to be used as a pseudo-replacement for subtyping. (See also discussions in Section 3.4 and in [11,13]).

13 One may here recall Cardelli’s noting, in [23, 25], of the ‘biological origin’ of OOP. This biological origin is the reason OO inheritance is called ‘inheritance’ in the first place.
the assignment `Animal a = new Cat()` is correctly allowed in nominally-typed OOP, but is wrongly disallowed in structurally-typed OOP.

To summarize, the code examples presented above demonstrate a fundamental difference between structurally-typed OOP and nominally-typed OOP from the perspective of OO developers. In structurally-typed OOP, where only class structure is inherited but not class contracts, `MultiSets` are `Sets` (contrary to their mathematical definition) and `Cats` are not `Animals` (contrary to their “biological definition”). In nominally-typed OOP, where class contracts are inherited (via class names) in addition to class structure, `MultiSets` are not `Sets` (in agreement with their mathematical definition) and `Cats` are `Animals` (in agreement with their “biological definition”).

In nominally-typed OOP whether subtyping is needed or not is indicated by the presence or absence of explicit inheritance declarations. Accordingly, the code examples above make it clear, more generally, that:

*Structurally-typed OOP sometimes forces subtyping when it is unneeded, and sometimes bars it when it is needed, while nominally-typed OOP only forces subtyping when it is explicitly needed, and bars it when, by omission, it is explicitly unneeded.*

This conclusion demonstrates a fundamental semantic and practical value of nominal information to OO developers of nominally-typed OO programming languages.

### 3.3.1 Spurious Binary Methods

A lesser-recognized problem with structurally-typed OOP, which is also related to binary methods, is the fact that, in a pure structurally-typed OO language (*i.e.*, one with no nominal typing features), a class like `Animal` cannot have a method like, say,

```java
void playWith(Animal a)
```

that keeps having the same signature in its subclass `Cat` and any other subclasses of class `Animal`. Pure structurally-typed OOP *always* treats a binary method any method inside a class that takes an argument that has the same type as that of the class the method is declared in. This causes methods like `playWith` in class `Animal`, whose semantics is *not* that of true binary methods, to be mistaken as ones, and thus, in subclass `Cat`, for example, the `playWith` method will have the restrictive signature

```java
void playWith(Cat a)
```

(allowing `Cats` to play only with other `Cats` but not with other `Animals`.)

We call this so-far-unrecognized problem with structural typing as the problem of ‘spurious binary methods’ (or, ‘false binary methods’), since a method is inadvertently considered as being a binary method when it should not be. Nominally-typed OO languages do not suffer from this problem, because nominally-typed OO languages treat any such method as a regular (*i.e.*, non-binary) method, and thus the signature of the method does not change upon inheritance in a nominally-typed OO language.

### 3.4 Nominal Typing, Type Names, Recursive Types and Binary Methods

Based on the discussion in the previous sections, a fundamental technical difference between nominally-typed OO languages and structurally-typed OO languages clearly lies in how the two approaches of typing OO languages differently view and treat *type names*.

In structurally-typed OO languages, type names are viewed as being names for type variables that abbreviate type expressions (*i.e.*, are “shortcuts”). As such type names in structurally-typed OO languages

---

14So as to allow `Cats` to play with `Dogs` and `Mouses` (*i.e.*, mice!), for example.

15In nominally-typed OOP, ‘F-bounded Generics’ (as used, for example, to define the generic class `Enum` in Java [43, 44]) offers a somewhat better alternative—if also not a fully satisfactory one—to support true binary methods, while keeping the identification between inheritance and subtyping. Based on some preliminary research we made, we expect future research to offer a more satisfactory alternative for supporting true binary methods in nominally-typed OO languages—hopefully a fully satisfactory alternative. (Also see related discussion close to the end of Section 3.4.)
are useful, and are even necessary for defining recursive type expressions. As variable names, however, recursive type names in structurally-typed OO languages (such as the name of a class when used inside the definition of the class, which gets interpreted as ‘self-type’) get rebound to different types upon inheritance, and they get rebound to types that, if they were subtypes, could break the contravariant subtyping rule of method parameter types and thus break the type safety of structurally-typed OO languages. Structurally-typed OO languages resolve this situation by breaking the one-to-one correspondence between inheritance and subtyping as we demonstrated in the earlier code examples in Section 3.2 and Section 3.3.

In nominally-typed OO languages, however, nominality of types means type names are viewed as part of the identity and meaning of type expressions given the association of type names with public class contracts. This means that class names cannot be treated as variable names. Accordingly, in a nominally-typed OO program type names have fixed meanings that do not change upon inheritance. Further, the fixed type a type name is bound to in a nominally-typed OO program does not break the contravariant subtyping of method parameters when the method and its type get inherited by subclasses, thus not necessitating breaking the identification between inheritance and subtyping as we demonstrated by the earlier code examples in Section 3.2 and Section 3.3.

In class-based OOP, a class can directly refer to itself (using class names) in the signature of a field, or that of a method parameter or return value. This kind of reference is called a self-reference, a recursive reference, or, sometimes, a circular reference. Also, mutually-dependent classes, where a class refers to itself indirectly (i.e., via other classes), are allowed in class-based OOP. This kind of reference inside a class, indirectly referencing itself, is called an indirect self-reference, a mutually-recursive reference, or, a mutually-circular reference.

As Pierce [63] noted, nominally-typed OO languages allow readily expressing circular (i.e., mutually-dependent) class definitions. Since objects in mainstream OOP are characterized as being self-referential values (are ‘self-aware,’ or ‘autognostic’ according to Cook [53]), and since self-referential values can be typed using recursive types [52], there is a strong and wide need for circular class definitions in OOP. As such, direct and indirect circular type references are quite common in mainstream OOP [63]. The ease by which recursive typing can be expressed in nominally-typed OO languages is one of the main advantages of nominally-typed OOP. According to Pierce [63, p.253],

‘The fact that recursive types come essentially for free in nominal systems is a decided benefit of nominally-typed OO languages.’

As a demonstration of the influence of views of self-referential classes on properties of OO type systems, when nominal and structural domain-theoretic models of OOP are compared (as done in brief, e.g., in [8, 10], and in detail, e.g., in [11]), it is easy to see that self-referential classes are viewed differently by nominal models of OOP than by structural models and that these different views of self-referential classes, in particular, make nominal domain-theoretic models of OOP lead to a simple mathematical proof of the identification between type inheritance and subtyping—a different conclusion than the one reached based on structural models. (In particular, the inclusion of class signature constructs in NOOP led to the simplicity of the mathematical proof of this identification. See [8, 11, 13] for more details.)

Aside from theory, the difference between the nominal and the structural views of type names in OOP demonstrates itself most prominently, in practice, in the different support and the different treatment provided by nominally-typed OO languages and by structurally-typed OO languages to “binary methods”. As mentioned in Section 3.3 a “binary method” is a method that takes a parameter or more of the same type as the class the method is declared in [22]. The problem of binary methods and requiring them to be supported in OO languages was a main factor behind structural models of OOP leading to not identifying type inheritance with subtyping. Structurally-typed OO languages, given their view of type names as type variable names that can get rebound, require the type of the argument of a method,
when identified as a binary method and upon inheritance of the method, to be that of the type corresponding to the subclass.

Nominally-typed OO languages, on the other hand, with their fixed interpretation of type names, offer a somewhat middle-ground solution between totally avoiding binary methods and overly embracing them as pure structurally-typed OO languages do. Nominally-typed OO languages treat a method taking in an argument of the same class as that in which the method is declared like any other method, needing no special treatment. Nominally-typed OOP thus does not quite support binary methods, but, for good reasons (i.e., so as to not break the identification of inheritance of contracts with subtyping nor lose other advantages of nominal typing), offers only a good approximation to binary methods. Given that the meaning of types names in nominally-typed OO languages does not change upon inheritance, these languages provide methods whose type, upon inheritance, only approximates that of true binary methods: The type of the input parameter of a method that approximates a binary method is guaranteed to be a supertype of its type if it were a true binary method. Given that the type of the parameter does not change in subclasses, the degree of approximation gets lesser the deeper in the inheritance hierarchy the method gets inherited.

In light of the ‘spurious binary methods’ problem we uncovered in structural OO type systems (see Section 3.3), we believe providing approximations to binary methods is a smart design choice by nominal OO type systems, even if it is likely that avoiding spurious binary methods may have not been consciously intended. It should also be noted that the problem of spurious binary methods provides justification for nominally-typed OO languages being cautious about fully embracing binary methods by treating a method that looks like a binary method as indeed being one.

Also, as we hinted to in earlier sections, in our opinion structural typing having arguably better support for binary methods does not justify using structural OO typing, since structural type systems have their own problems in their support of binary methods (i.e., the problem of spurious binary methods). We conjecture that F-bounded generics, or some other notion\footnote{For example, “implicit self-type-variables”, e.g., \texttt{This/Self}, which are implicit type variables because they do not get included in class signatures, similar to “implicit self-variables”, e.g., \texttt{this/self}, which are not included in method signatures.} may provide a better solution for binary methods in nominally-typed (and possibly also in structurally-typed OOP) that does not require breaking the identification of inheritance with subtyping (and thus does not require sacrificing the closeness of nominal typing/subtyping to semantic and behavioral typing/subtyping and other advantages of nominal typing). In light of the ‘spurious binary methods’ problem, and requiring no explicit use of generics, in our opinion a better approach towards supporting binary methods in mainstream OO languages might be by allowing developers to explicitly mark or flag binary methods as being such, or, even more precisely, to allow developers to mark specific parameters of methods as being parameters that need to be treated as those of binary methods.

As to “hybrid” OO languages, which add (some) structural typing features to nominally-typed OO languages\footnote{Due to problems with supporting recursive types mentioned above, we believe most of these “hybrid” languages do not support recursive structural types, for example.}, or vice versa, we conjecture that the useful part of the claimed “flexibility” of structural typing may be possible to achieve in nominally-typed OO languages by supporting a separate notion of ‘contract names,’ thereby splitting class names from contract names, then allowing classes to additionally define themselves as satisfying supercontracts of other already-defined (sub)classes. We have not explored this suggestion further however, since we believe it may complicate nominal OO type systems. But we believe that, if flexibility is an absolute necessity, then splitting class names from contract names may be a suggestion worthy of investigation. We believe this suggestion to be a more viable option—simpler to reason about and more in agreement with the nominal spirit of nominally-typed OO languages—than using multiple dispatch \cite{30,18,31}, which was discussed in \cite{22} as a possible solution to the problem of binary methods, and also more viable than creating hybrid languages. We believe that having an OO type system be both nominally and structurally typed, as
in [38, 02, 42, 54, 55, 01, 4], makes the type system very complex (and probably even lends its “hybrid” features unusable.)

4 Concluding Remarks

In this essay we added to earlier efforts that aimed to demonstrate the semantic value of nominal typing, particularly the association of class names with behavioral class contracts, by making a technical comparison between nominal OO type systems and structural OO type systems. Recently, a domain-theoretic model of nominally-typed OOP, namely NOOP, was also compared to models of structurally-typed OOP. These comparisons provide a clear and deep account for the relation between nominal and structural OO type systems that, due to earlier lack of a domain-theoretic model of nominally-typed OOP, has not been presented before, and they should help further demonstrate, to OO PL researchers, the value of nominal typing and nominal subtyping to mainstream OO developers and language designers, and instill in them a deeper appreciation of it.

In the essay we particularly noted that nominal typing prevents types that structurally look the same from being confused as being the same type. Since some objects having the same structure does not necessarily imply these objects have the same behavior, nominal typing identifies types only if they have the same class names information (nominal information) and thus only if they assert maintaining the same contract and not just assert having the same structural interface. Thus, in nominally-typed OOP objects having the same class type implies them asserting they maintain the same contracts, and them asserting they maintain the same contracts implies them having the same type.

Similarly, nominal subtyping allows subtyping relations to be decided based on the refinement of contracts maintained by the objects, not just based on the refinements of their structure. By inclusion of contracts in deciding the subtyping relation, nominal subtyping thus also prevents types that are superficially (i.e., structurally) similar from being confused as being subtypes. Since the similarity of structure does not necessarily imply the similarity of behavior, in nominally-typed OOP type inheritance implies refined contracts, and refined contracts imply subsumption between class types, and vice versa (i.e., in nominally-typed OOP, subsumption between class types implies refined contracts, implying type inheritance.)

Putting these facts together, it is clear that in nominally-typed OOP different class names information implies different contracts/types and different contracts/types imply different class names information. This identification of types with contracts, and of subtyping with inheritance of contracts, makes nominal typing and nominal subtyping closer to semantic typing and semantic subtyping.

In the essay we thus stressed the practical value of nominal typing in mainstream OOP by particularly showing

1. The value of nominal subtyping, at compile time and at runtime, in respecting behavioral contracts and thus respecting design intents,

2. The value of the resulting identification between inheritance and subtyping in providing a simpler conceptual model of OO software and of OO software components, leading to a simpler design process of OO software, and

3. The value of making recursive types readily expressible, this being necessary for the static typing of “autognostic” objects.

Our comparison also revealed the problem of ‘spurious binary methods,’ so far an unrecognized problem in structurally-typed OO languages.

Further, the recent comparison of nominal and structural denotational models of OOP demonstrates them having different views of fundamental notions of mainstream OOP, namely of objects, of type names, of object/class types, of subtyping and of the relation between subtyping and type inheritance. In particular, this comparison demonstrates that an object in mainstream nominally-typed OOP is a record together with nominal information, that class types are record types whose elements (i.e., objects/class instances) additionally respect statements of class con-
tracts, and that type inheritance is correctly identified with nominal subtyping.

Table 3 on the following page summarizes the main differences between nominal typing and structural typing we pointed out in this essay.

We hope the development of mathematical models of nominally-typed OOP and the comparisons presented in this essay and elsewhere are significant steps in providing a full account of the relation between nominal and structural OO type systems. We further hope this essay clearly explains the rationale behind our belief that the significant practical value and the significant semantic value of nominal typing are the reasons for industrial-strength mainstream OO software developers correctly choosing to use nominally-typed OO languages. We believe that having a clear view of the rationale behind many OO developers’ preference of nominally-typed OO languages, and having a more accurate technical and mathematical view of nominally-typed OO software, present programming languages researchers with better chances for progressing mainstream OO languages and for making PL research relevant to more OO language designers and more mainstream OO software developers.\(^\text{18}\)

Finally, we believe a clearer understanding and a deeper appreciation of a key semantic advantage of nominal OO typing over structural OO typing can help remedy the existing schism between OO PL researchers on one hand and OO developers and OO language designers on the other hand, offering thereby better chances for progressing mainstream OO languages. In particular, we believe future foundational OO PL research, to further its relevance to mainstream OOP, should be based less on structural models of OOP and more on nominal ones instead.

**References**

[1] C# language specification, version 3.0. http://msdn.microsoft.com/vcsharp, 2007.

[2] ISO/IEC 14882:2011: Programming Languages: C++. 2011.

[3] The Scala programming language. www.scala-lang.org, 2014.

[4] The Go programming language. www.golang.org, 2015.

[5] The TIOBE index. http://www.tiobe.com/index.php/content/paperinfo/tpci/index.html, 2016.

[6] Martin Abadi and Luca Cardelli. A semantics of object types. In *Proc. LICS’94*, 1994.

[7] Martin Abadi and Luca Cardelli. *A Theory of Objects*. Springer-Verlag, 1996.

[8] Moez A. AbdelGawad. *NOOP: A Mathematical Model of Object-Oriented Programming*. PhD thesis, Rice University, 2012.

[9] Moez A. AbdelGawad. An overview of nominal-typing versus structural-typing in object-oriented programming (with code examples). Technical report, arXiv.org:1309.2348 [cs.PL], 2013.

[10] Moez A. AbdelGawad. A domain-theoretic model of nominally-typed object-oriented programming. *Journal of Electronic Notes in Theoretical Computer Science (ENTCS)*, DOI: 10.1016/j.entcs.2014.01.002., 301:3–19, 2014.

[11] Moez A. AbdelGawad. A comparison of NOOP to structural domain-theoretic models of object-oriented programming. Preprint available at http://arXiv.org/abs/1603.08648, 2016.
|                                | Nominally-Typed OOP                        | Structurally-Typed OOP                      |
|--------------------------------|-------------------------------------------|--------------------------------------------|
| **Object Interfaces**          | Nominal; Include class names               | Structural; Do not include class names     |
| **Contracts**                  | Included (via class names) in the meaning of objects, of their interfaces and of their types | Ignored in the meaning of objects, of object interfaces, and of object types |
| **Types of Objects**           | Class types                                | Record types                               |
| **Object Type Expressions**    | Class signatures                           | Record type expressions                    |
| **Type Reification/Nominality**| Class signatures, as object types, are included in object meanings | Objects do not carry their types as part of object meanings |
| **Type Names**                 | Class names, being associated with public class contracts, are used as type names | Type names are abbreviations/ synonyms for type expressions (with no inherent fixed meaning) |
| **Meaning of Type Names**      | Fixed. Cannot be rebound upon inheritance | Can be rebound upon inheritance            |
| **(Type) Inheritance**         | Includes inheritance of class contracts    | Ignores behavioral class contracts         |
| **Subtyping**                  | Respects contracts; respects (type) inheritance | Ignores behavioral class contracts         |
| **(Type) Inheritance versus Subtyping** | One-to-one correspondence                  | Two relations independent                  |
| **OO Software Design Mental Model** | Simple; Inheritance hierarchy = Subtyping hierarchy | Complex; An inheritance hierarchy and a separate, independ’nt subtyping hierarchy |
| **Binary Methods**             | Not supported. Approximations provided     | Fully supported (including false ones)     |
| **Spurious and Missing Subsumption** | Neither can exist                           | Both can exist                             |
| **Spurious Bin. Methods**      | Cannot exist                               | Can exist                                  |
| **Recursive Types**            | Readily and naturally expressed           | Special constructs needed for explicit expression |
| **Typing and Subtyping**       | Closer to semantic/behavioral typing and subtyping | Further from semantic/behavioral typing and subtyping |

Table 3: OO Nominal-Typing vs. OO Structural-Typing
[12] Moez A. AbdelGawad. Towards understanding generics. Technical report, arXiv:1605.01480 [cs.PL], 2016.

[13] Moez A. AbdelGawad and Robert Cartwright. In nominally-typed OOP, objects are not mere records and inheritance Is subtyping. Submitted for journal publication, 2016.

[14] Jonathan Aldrich. The power of interoperability: Why objects are inevitable. In Proceedings of the 2013 ACM International Symposium on New Ideas, New Paradigms, and Reflections on Programming & Software, Onward! 2013, pages 101–116, New York, NY, USA, 2013. ACM.

[15] Joseph A. Bank, Barbara Liskov, and Andrew C. Myers. Parameterized types and Java. Technical report, 1996.

[16] Joshua Bloch. Effective java programming language guide, sun microsystems. Inc., Mountain View, CA, 2001.

[17] Joshua Bloch. Effective Java. Prentice Hall PTR, 2008.

[18] John Boyland and Giuseppe Castagna. Parasitic methods: An implementation of multi-methods for Java. In OOPSLA, 1997.

[19] G. Bracha and D. Griswold. Strongtalk: type-checking Smalltalk in a production environment. In OOPSLA’93, pages 215–230, 1993.

[20] Gilad Bracha, Martin Odersky, David Stoutamire, and Philip Wadler. Making the future safe for the past: Adding genericity to the Java programming language. In Craig Chambers, editor, ACM Symposium on Object-Oriented Programming: Systems, Languages and Applications (OOPSLA), volume 33, pages 183–200, Vancouver, BC, October 1998. ACM, ACM SIGPLAN.

[21] K. Bruce, A. Schuett, R. van Gent, and A. Fiech. PolyTOIL: A type-safe polymorphic object-oriented language. ACM Transactions on Programming Languages and Systems, 25(2):225–290, 2003.

[22] Kim Bruce, Luca Cardelli, Giuseppe Castagna, The Hopkins Objects Group, Gary Leavens, and Benjamin C. Pierce. On binary methods. Theory and Practice of Object Systems, 1994.

[23] Kim B. Bruce. Foundations of Object-Oriented Languages: Types and Semantics. MIT Press, 2002.

[24] Luca Cardelli. A semantics of multiple inheritance. In Proc. of the internat. symp. on semantics of data types, volume 173, pages 51–67. Springer-Verlag, 1984.

[25] Luca Cardelli. A semantics of multiple inheritance. Inform. and Comput., 76:138–164, 1988.

[26] Luca Cardelli. Structural subtyping and the notion of power type. In ACM Proceedings of POPL, 1988.

[27] Luca Cardelli, James Donahue, Lucille Glassman, Mick Jordan, Bill Kalsow, and Greg Nelson. Modula-3 Report (Revised), volume 52. Digital Systems Research Center, 1989.

[28] Robert Cartwright and Moez A. AbdelGawad. Inheritance Is subtyping (extended abstract). In The 25th Nordic Workshop on Programming Theory (NWPT), Tallinn, Estonia, 2013.

[29] Robert Cartwright and Jr. Steele, Guy L. Compatible genericity with run-time types for the Java programming language. In Craig Chambers, editor, ACM Symposium on Object-Oriented Programming: Systems, Languages and Applications (OOPSLA), volume 33, pages 201–215, Vancouver, BC, October 1998. ACM, ACM SIGPLAN.

[30] C. Chambers. Object-oriented multi-methods in Cecil. In ECOOP, 1992.

[31] C. Clifton, T. Millstein, G. Leavens, and C. Chambers. MultiJava: Design rationale, compiler implementation and applications. ACM Transactions on Programming Languages and Systems, 28(3):517–575, 2006.
[32] William R. Cook. *A Denotational Semantics of Inheritance*. PhD thesis, Brown Univ., 1989.

[33] William R. Cook. On understanding data abstraction, revisited. *ACM, 2009.*

[34] William R. Cook, Walter L. Hill, and Peter S. Canning. Inheritance is not subtyping. In *POPL’90 Proceedings*, 1990.

[35] William R. Cook and Jens Palsberg. A denotational semantics of inheritance and its correctness. In *ACM Symposium on Object-Oriented Programming, Systems, Languages and Applications (OOPSLA)*, pages 433–444, 1989.

[36] Sophia Drossopoulou, Susan Eisenbach, and Sarfraz Khurshid. Is the java type system sound? *TAPOS*, 5(1):3–24, 1999.

[37] Mohamed Fayad and Douglas C. Schmidt. Object-oriented application frameworks. *Commun. ACM*, 40(10):32–38, October 1997.

[38] Robert Bruce Findler, Matthew Flatt, and Matthias Felleisen. Semantic casts: Contracts and structural subtyping in a nominal world. In *ECOOP 2004–Object-Oriented Programming*, pages 365–389. Springer, 2004.

[39] K. Fisher and J. Reppy. The design of a class mechanism for Moby. In *PLDI*, 1999.

[40] Matthew Flatt, Shriram Krishnamurthi, and Matthias Felleisen. Classes and mixins. In *Proceedings of the 25th ACM SIGPLAN-SIGACT symposium on Principles of programming languages*, pages 171–183. ACM, 1998.

[41] Matthew Flatt, Shriram Krishnamurthi, and Matthias Felleisen. A programmer’s reduction semantics for classes and mixins. In *Formal syntax and semantics of Java*, pages 241–269. Springer, 1999.

[42] J. Gil and I. Maman. Whiteoak: Introducing structural subtyping in Java. In *OOPSLA*, 2008.

[43] James Gosling, Bill Joy, Guy Steele, and Gilad Bracha. *The Java Language Specification*. Addison-Wesley, 2005.

[44] James Gosling, Bill Joy, Guy Steele, Gilad Bracha, and Alex Buckley. *The Java Language Specification*. Addison-Wesley, 2014.

[45] Atsushi Igarashi, Benjamin C. Pierce, and Philip Wadler. Featherweight Java: A minimal core calculus for Java and GJ. *ACM Transactions on Programming Languages and Systems*, 23(3):396–450, May 2001.

[46] Reto Kramer. Examples of Design by Contract in Java. In *Design and Components - Object World - Berlin*, 1999.

[47] Angelika Langer. The Java Generics FAQ. www.angelikalanger.com/GenericsFAQ/Java-GenericsFAQ.html, 2015.

[48] X. Leroy, D. Doligez, J. Garrigue, D. Rémy, and J. Vuillon. The Objective Caml system. Available at http://caml.inria.fr/.

[49] Barbara Liskov. Keynote address-data abstraction and hierarchy. In *ACM Sigplan Notices*, volume 23, pages 17–34. ACM, 1987.

[50] Barbara H Liskov and Jeannette M Wing. A behavioral notion of subtyping. *ACM Transactions on Programming Languages and Systems (TOPLAS)*, 16(6):1811–1841, 1994.

[51] David B. MacQueen. Should ML be object-oriented? *Formal Aspects of Computing*, 13:214–232, 2002.

[52] David B. MacQueen, Gordon D. Plotkin, and R. Sethi. An ideal model for recursive polymorphic types. *Information and Control*, 71:95–130, 1986.

[53] Boris Magnusson. Code reuse considered harmful, 1991.

[54] Donna Malayeri and Jonathan Aldrich. Integrating nominal and structural subtyping. In *ECOOP 2008–Object-Oriented Programming*, pages 260–284. Springer, 2008.
[55] Donna Malayeri and Jonathan Aldrich. Is structural subtyping useful? an empirical study. In ESOP, 2009.

[56] Erik Meijer and Peter Drayton. Static typing where possible, dynamic typing when needed: The end of the cold war between programming languages. In OOPSLA, 2004.

[57] Bertrand Meyer. Applying ‘design by contract’. Computer, 25(10):40–51, 1992.

[58] Bertrand Meyer. Object-Oriented Software Construction. Prentice Hall, 1995.

[59] R. Milner, M. Tofte, R. Harper, and D. MacQueen. The Definition of Standard ML (Revised). MIT Press, 1997.

[60] Tobias Nipkow and David Von Oheimb. Java
tight is type-safe–definitely. In Proceedings of the 25th ACM SIGPLAN-SIGACT symposium on Principles of programming languages, pages 161–170. ACM, 1998.

[61] Martin Odersky. The scala language specification, v. 2.7. http://www.scala-lang.org, 2009.

[62] Klaus Ostermann. Nominal and structural subtyping in component-based programming. Journal of Object Technology, 7(1):121–145, 2008.

[63] Benjamin C. Pierce. Types and Programming Languages. MIT Press, 2002.

[64] Benjamin C. Pierce. Types and programming languages: The next generation. LICS’03, 2003.

[65] Harry H Porter III. Separating the subtype hierarchy from the inheritance of implementation. Journal of Object-Oriented Programming, 4(6):20–29, 1992.

[66] Anthony J. H. Simons. The theory of classification, part 1: Perspectives on type compatibility. Journal of Object Technology, 1(1):55–61, May-June 2002.