

SFJ: An implementation of Semantic Featherweight Java [★]

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Abstract. There are two approaches to defining subtyping relations: the *syntactic* and the *semantic* approach. In semantic subtyping, one defines a model of the language and an interpretation of types as subsets of this model. Subtyping is defined as inclusion of subsets denoting types. An orthogonal subtyping question, typical of object-oriented languages, is the *nominal* versus the *structural* subtyping. Dardha *et al.* [9,10] defined boolean types and semantic subtyping for Featherweight Java (FJ) and integrated both nominal and structural subtyping, thus exploiting the benefits of both approaches. However, these benefits were illustrated only at a theoretical level, but not exploited practically.

We present SFJ—Semantic Featherweight Java, an implementation of FJ which features boolean types and semantic subtyping and integrates nominal as well as structural subtyping. The benefits of SFJ, illustrated in the paper and the accompanying video (with audio/subtitles) [26], show how static typechecking of boolean types and semantic subtyping gives higher guarantees of program correctness, more flexibility and compactness of program writing.

Keywords: Nominal subtyping · Structural subtyping · Semantic Featherweight Java · Object-oriented languages · Boolean types · Type theory.

1 Introduction

There are two approaches to defining subtyping relations: the *syntactic* and the *semantic* approach. Syntactic subtyping [18] is more mainstream in programming languages and is defined by means of a set of formal deductive subtyping rules. Semantic subtyping [6,5,11] is more recent and less known: one defines a formal model of the language and an interpretation of types as subsets of this model. Then, subtyping is defined as set inclusion of subsets denoting types.

Orthogonally, for object-oriented languages there are two approaches to defining subtyping relations: the *nominal* and the *structural* approach [19,20]. Nominal subtyping is based on declarations by the developer and is *name*-based: “A is

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a subtype of B if and only if it is declared to be so, that is if the class A extends (or implements) the class (or interface) B ". Structural subtyping instead is based on the *structure* of a class, its fields and methods: "a class A is a subtype of a class B if and only if the fields and methods of A are a superset of the fields and methods of B , and their types in A are subtypes of the types in B ". Intuitively, extending a class with more fields and methods results in a smaller set of inhabitants for that class. For example, the set of objects of a class *Student* is smaller than the set of objects of a class *Person* as each *Student* is a *Person*, but not the other way around. Hence, *Student* is a structural subtype of *Person*, even if it is not declared to be so.

Dardha *et al.* [9,10] define boolean types—based on set-theoretic operations such as **and**, **not**, **or**—and semantic subtyping for *Featherweight Java* (FJ) [16]. This approach allows for the integration of both nominal and structural subtyping in FJ, bringing in higher guarantees of program correctness, flexibility and compactness in program writing. Unfortunately, these benefits were only presented at a theoretical level and not exploited practically, due to the lack of an implementation of the language and its types and type system.

In this paper, we present SFJ—*Semantic Featherweight Java* § 3, an implementation of FJ with boolean types and semantic subtyping. In SFJ the developer has a larger and more expressive set of types, by using boolean connectives **and**, **not**, **or**, with the expected set-theoretic interpretation. On the other hand, this added expressivity does not add complexity. Rather the opposite is true, as the developer has an easier, more compact and elegant way of programming. SFJ integrates both structural and nominal subtyping, and the developer can choose which one to use. Finally, as discussed in Dardha *et al.* [10, §8.4], thanks to semantic subtyping, we can easily encode in SFJ standard programming constructs and features of the full Java language, such as lists, or overloading classes via multimethods [4], which are missing in FJ, thus making SFJ a more complete language closer to Java.

Example 1 (Polygons). This will be our running example both in the paper and in the tool video [26] to illustrate the benefits of boolean types and semantic subtyping developed by Dardha *et al.* [9,10] and implemented as SFJ.

Consider the set of polygons, such as triangles, squares and rhombuses given by a class hierarchy. We want to define a method *diagonal* that takes a polygon and returns the length of its longest diagonal. This method makes sense only if the polygon passed to it has at least four sides, hence triangles are excluded. In Java this could be implemented in the following ways:

```
class Polygon {...}
class Triangle extends Polygon {...}
class Other_Polygons extends Polygon {
    double diagonal(Other_Polygons shape) {...}
    ...
}
class Square extends Other_Polygons {...}
class Rhombus extends Other_Polygons {...}
```

Or by means of an interface *Diagonal*:

```
public interface Diagonal {
    double diagonal(Polygon shape);
}
class Polygon {...}
class Triangle extends Polygon {...}
class Square extends Polygon implements Diagonal {...}
class Rhombus extends Polygon implements Diagonal {...}
...
```

Now, suppose our class hierarchy is such that *Polygon* is the parent class and all other geometric figures extend *Polygon*, which is how one would naturally define the set of polygons. Suppose the class hierarchy is given and is part of legacy code, which cannot be changed. Then again, a natural way to implement this in Java is by defining the method *diagonal* in the class *Polygon* and using an **instanceof**, for example, inside a **try-catch** construct. Then, an exception would be thrown at runtime, if the argument passed to the method is a triangle.

We propose a more elegant solution, by combining boolean types and semantic subtyping, where only static typechecking is required and we implement this in SFJ [26]: it is enough to define a method *diagonal* that has an argument of type *Polygon* **and not** *Triangle*, thus allowing the typechecker to check at compile time the restrictions on types:

```
class Polygon {...}
class Triangle extends Polygon {...}
class Square extends Polygon {...}
class Rhombus extends Polygon {...}
...
class Diagonal {
    ...
    double diagonal((Polygon and not Triangle) shape){...}
}
```

We can now call *diagonal* on an argument of type *Polygon*: if the polygon is **not** a *Triangle*, then the method returns the length of its longest diagonal; otherwise, if the polygon is a triangle, then there will be a type error at compile time.

Structure of the paper: § 2 details the technical developments behind semantic subtyping and its properties. § 3 details the design and implementation of SFJ. § 4 concludes the paper.

2 Background

The technical developments behind semantic subtyping and its properties are complex, however, they are completely transparent to the programmer. The

framework is detailed and proved correct in the relevant work by Dardha *et al.* [9,10], and SFJ builds on that framework.

In this section we will briefly detail the types and terms of SFJ.

2.1 Types

The syntax of types τ is defined by the following grammar:

$$\begin{array}{ll} \tau ::= \alpha \mid \mu & \text{Types} \\ \alpha ::= \mathbf{0} \mid \mathbb{B} \mid [\widetilde{l} : \tau] \mid \alpha \textbf{ and } \alpha \mid \textbf{not } \alpha & \text{Field types } (\alpha\text{-types}) \\ \mu ::= \alpha \rightarrow \alpha \mid \mu \textbf{ and } \mu \mid \textbf{not } \mu & \text{Method types } (\mu\text{-types}) \end{array}$$

The α -types are used to type fields and the μ -types are used to type methods. Type $\mathbf{0}$ is the empty type. Type \mathbb{B} denotes the *basic* types, such as integers, booleans, etc. Record types $[\widetilde{l} : \tau]$, where \widetilde{l} is a sequence of disjoint labels, are used to type objects. Arrow types $\alpha \rightarrow \alpha$ are used to type methods.

The boolean connectives **and** and **not** in the α -types and μ -types have their expected set-theoretic meanings. We let $\alpha \setminus \alpha'$ denote α **and** (**not** α'), and α **or** α' denote **not**(**not** α **and** (**not** α')).

2.2 Terms

The syntax of terms is defined by the following grammar and is based on the standard syntax of terms in FJ [16]:

$$\begin{array}{ll} \text{Class declaration} & L ::= \textbf{class } C \textbf{ extends } C \{ \widetilde{\alpha} a; K; \widetilde{M} \} \\ \text{Constructor} & K ::= C (\widetilde{\alpha} x) \{ \textbf{super}(\widetilde{x}); \widetilde{\textbf{this}.a} = \widetilde{x}; \} \\ \text{Method declaration} & M ::= \alpha m (\alpha x) \{ \textbf{return } e; \} \\ \text{Expressions} & e ::= x \mid c \mid e.a \mid e.m(e) \mid \textbf{new } C(\widetilde{e}) \end{array}$$

We assume an infinite set of names, with some special names: *Object* denotes the root class, **this** denotes the current object and **super** denotes the parent object. We let A, B, \dots range over classes; a, b, \dots over fields; m, n, \dots over methods and x, y, z, \dots over variables.

A program (\widetilde{L}, e) is a pair of a sequence of class declarations \widetilde{L} , giving rise to a class hierarchy as specified by the inheritance relation, and an expression e to be evaluated. A class declaration L specifies the name of the class, the name of the parent class it extends, its typed fields, the constructor K and its method declarations M . The constructor K initialises the fields of the object by assigning values to the fields inherited by the super-class and to the fields declared in the current **this** class. A method declaration M specifies the signature of the method, namely the return type, the method name and the formal parameter as well as the body of the method. Notice that in our theoretical development we use unary methods, without loss of generality: tuples of arguments can be modelled by an object that instantiates a “special” class containing as fields all the needed arguments. Expressions e include variables, constants, field accesses, method invocations and object creations.

On multimethods Since FJ is a core language, some features of the full Java are removed, such as overloading methods. In our framework, by leveraging the expressivity of boolean connectives and semantic subtyping, we are able to restore overloading, among other features [10, §8.4]. We can thus model *multimethods*, [4], which according to the authors is “*very clean and easy to understand [...] it would be the best solution for a brand new language*”. As an example, taken from Dardha *et al.* [9,10], consider the following class declarations:

```

class A extends Object {
    int length (string s){ ... }
}

class B extends A {
    int length (int n){ ... }
}

```

Method *length* has type **string** \rightarrow **int** in class *A*. However, because class *B* extends class *A*, *length* has type (**string** \rightarrow **int**) and (**int** \rightarrow **int**) in class *B*, which can be simplified to (**string or int**) \rightarrow **int**.

Following FJ [16], we rule out ill-formed programs, such as declaring a constructor named *B* within a class named *A*; or multiple fields or methods having the same name; or fields having the same type as the type of the class they are defined in.

3 SFJ: Design and Implementation

3.1 Valid type definitions

Since we want to use types τ in practice in SFJ, we restrict them to *finite trees* whose leaves are basic types \mathbb{B} § 2.2 with no cycles. For example, a recursive type $\alpha = [a : \alpha]$ denotes an infinite program tree **new** *C*(**new** *C*(\dots)), hence we rule it out as it is not inhabitable. Similarly, the types $\alpha = [b : \beta]$, $\beta = [a : \alpha]$ create a cycle and thus would not be inhabitable. Notice that the above types can be defined in Java. These types can be inhabited by assigning *null* to all fields, but are not useful in practise.

«««< HEAD SFJ is implemented using ANTLR [22]. We start by defining the grammar of the language in Extended Backus-Naur Form (EBNF), following § 2.1 and by running ANTLR, we can automatically generate a parser for SFJ and extend it in order to implement the required checks for our types and type system. Running the parser on an SFJ program returns an abstract syntax tree (AST) of that program.

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Input : *classes*, the set of classes marked *resolved* if their fields contain only basic types, *unresolved* otherwise.

Output : *True* if all classes are valid type definitions, *False* otherwise.

```

1 begin
2   do
3     resolutionOccured  $\leftarrow$  False
4     for class that is unresolved in classes do
5       resolved  $\leftarrow$  True
6       for field in class that contains a class type do
7         if type of field is unresolved then
8           resolved  $\leftarrow$  False
9         end
10      end
11
12      if resolved = True then
13        class  $\leftarrow$  resolved
14        resolutionOccured  $\leftarrow$  True
15      end
16    end
17    while resolutionOccured = True
18
19    if not all classes are resolved then
20      return False
21    else
22      return True
23    end
24 end

```

Algorithm 1: Validity Check for Type Definitions

Algorithm 1 checks if the type definitions in a program are valid, namely, if they are finite trees whose leaves are basic types with no cycles. At each iteration of the algorithm we can resolve at least one type, until all the types in the SFJ program are resolved, and return *True*. However, if there is at least one type unresolved, meaning there is a cycle in the type definition, we return *False*.

3.2 Building the semantic subtyping for SFJ

If Algorithm 1 returns *True*, meaning all type definitions in the program are valid, we can proceed to building the semantic subtyping for SFJ. Leveraging the interpretation of types as sets of values to define the semantic subtyping for FJ [9,10], in our implementation of SFJ we keep track of the semantic subtyping relation by defining a map from a type to the set of its subtypes, satisfying the property that the set of values of a subtype is included in the set of values of the type. We start with basic types and define *Universe* to be the set of all types.

The mapping for basic types is defined as follows.

$$\begin{aligned}
 \textit{Double} &= \{\textit{Double}, \textit{Float}, \textit{Int}, \textit{Short}, \textit{Byte}\} & \textit{Float} &= \{\textit{Float}, \textit{Short}, \textit{Byte}\} \\
 \textit{Long} &= \{\textit{Long}, \textit{Int}, \textit{Short}, \textit{Byte}\} & \textit{Int} &= \{\textit{Int}, \textit{Short}, \textit{Byte}\} \\
 \textit{Short} &= \{\textit{Short}, \textit{Byte}\} & \textit{Byte} &= \{\textit{Byte}\} \\
 \textit{Boolean} &= \{\textit{Boolean}\} & \textit{Void} &= \{\textit{Void}\} \\
 \textit{Universe} &= \{\textit{Double}, \textit{Float}, \textit{Long}, \textit{Int}, \\
 &\quad \textit{Short}, \textit{Byte}, \textit{Boolean}, \textit{Void}\}
 \end{aligned} \tag{3.1}$$

Note that *Int* is not a subtype of *Float* as a 32-bit *float* cannot represent the whole set of 32-bit *integer* values accurately and therefore *Int* is not fully set-contained in *Float*, however this is not the case for *Int* and *Double*. Similarly, *Long* is not a subtype of *Double*.

Algorithm 2 builds the semantic subtyping relation for all class types of an SFJ program by calling the function *generateRelation*. Given that classes are valid type definitions by Algorithm 1, we are guaranteed that Algorithm 2 will terminate. The semantic subtyping generated by Algorithm 2 is a preorder: it is reflexive and transitive. This is also illustrated by Mapping 3.1.

Some comments on Algorithm 2 will follow. In function *generateRelation* we iterate over the set of classes in an SFJ program. If the class currently being processed contains fields or methods not present in the subtyping relation (line 5), then we add the current class to the list of *unprocessed* classes (line 6), so we can process its fields and methods first. The set of unprocessed classes will then be inspected again in a recursive call (line 10). The next two functions of the algorithm, *addClass* and *checkSuperSet*, check subtyping for the current *class* being processed and update *relation*, which is a mapping from a type to its subtypes and originally only consists of entries from Mapping 3.1. In function *addClass(class)* we check if the type *class* is a subtype of an existing type in *relation* (lines 15-18), as well as the opposite, meaning if *class* is a supertype of an existing type in *relation* (line 19). In order to do so *checkSuperSet* checks all fields (lines 28-39) and all methods (lines 40-51) in *class* and compares them with an *existingClass* in *relation*. If a subtyping relation is established, then it is added to *relation* (line 53). Finally, upon returning from *checkSuperSet*, we also add *class* to its own relation (line 21) to satisfy reflexivity and to *Universe* (line 22), which is a supertype of all types.

It is worth noticing that the subtyping algorithm finds all nominal and structural subtypes of a given type. This is due to the fact that all pairs of types are inspected. Recall from § 1 that nominal subtyping is name-based and given by the class hierarchy defined by the programmer, whether structural subtyping is structure-based and given by the set-inclusion of fields and methods. In particular, it is contra-variant with respect to this set-inclusion. Algorithm 2 finds all structural subtypes of a given class because it checks that its fields and methods are a superset of existing types in *relation*. On the other hand, it also finds all nominal subtypes because a class inherits all fields and methods of its superclass and as such its fields and methods are a superset of its superclass. This means

that checking for structural subtyping is enough because nominal subtyping will be captured due to inheritance of fields and methods.

3.3 Polygons: Continued

Let us illustrate the subtyping algorithm with our *Polygons* Example 1. The algorithm generates the following subtyping relation, which also includes the subtyping relation for basic types defined in the first step.

$$\begin{aligned} Polygon &= \{Polygon, Triangle, Square, Rhombus\} & Triangle &= \{Triangle\} \\ Square &= \{Square\} & Rhombus &= \{Rhombus\} & Diagonal &= \{Diagonal\} \end{aligned}$$

Recall method *diagonal* in class *Diagonal*, we can see that the result of the set operation on its parameter type gives the following set of polygons:

$$Polygon \text{ and not } Triangle = \{Polygon, Square, Rhombus\}$$

If we pass to *diagonal* an argument of type *Triangle*, as it is not contained in the computed set of subtypes, we get a typechecking error at compile time [26].

The subtyping algorithm finds all nominal and structural subtypes. It finds all nominal subtypes as they inherit all fields and methods of their super class, so are always guaranteed to be a superset. Similarly, given all pairs of types, the algorithm checks if one is a superset of the other, i.e., they share common fields and methods, and if so, they are related by structural subtyping. For example, type *empty* = [], will have all classes as structural subtypes.

Note that both approaches to subtyping have their drawbacks. Consider two structurally equivalent class/record types *coordinate* = [*x* : *int*, *y* : *int*, *z* : *int*] and *colour* = [*x* : *int*, *y* : *int*, *z* : *int*]. While structurally they can be used interchangeably in our type system, their “meaning” is completely different. Therefore, we lose some safety in our language as it is unlikely we would like to use a colour where we expect a coordinate, but in the eyes of the type-checker, it is correct.

Dardha *et al.*[10] suggest a possible extension to the language by including a *nominal* keyword that can be used in the class signature to indicate that this class should only be considered by the nominal component of the type system. This would allow us finer control over the type system and eliminate the previously mentioned problems. However, being optional, we argue this would create more bugs than problems it would solve, due to easily forgetting the keyword. For example with destructors in C++ classes, leaving out the *virtual* keyword of the parent class destructor in certain situations can lead to memory leaks. Instead a *structural* keyword could be introduced as an extension to the language which specifies that this class is allowed to have structural subtypes. A class with this keyword is not added to the subtyping relation of other structurally similar classes which are not marked *structural* as this would weaken the invariant conditions of that class.

On the other hand, with nominal subtyping in Java one can define an overridden method to perform the opposite logic to what the super class is expecting.

Input : *classes*, the set of classes in an SFJ program for which we have not yet defined the subtyping relation.
relation, the mapping of types to the set of subtypes, initially being Mapping 3.1.

```

1 begin
2   Function generateRelation(classes: List<Class>):
3     unprocessed : List < Class >  $\leftarrow$  []
4     for class in classes do
5       if addClass(class) = False then
6         | unprocessed.add(class)
7       end
8     end
9     if untyped  $\neq$  [] then
10      | generateRelation(unprocessed)
11    end
12  end
13
14  Function addClass(class: Class)  $\rightarrow$  boolean:
15    for existing class type in relation do
16      if checkSuperSet(class, existingClass) = False then
17        | return False
18      end
19      checkSuperSet(existingClass, class)
20    end
21    relation[class].add(class)
22    relation[Universe].add(class)
23    return True
24  end
25
26  Function checkSuperSet(class: Class, other: Class)  $\rightarrow$  boolean:
27    flag  $\leftarrow$  True
28    for field in class do
29      if field contains type not in relation then
30        | return False
31      end
32      if other does not contain field then
33        | flag  $\leftarrow$  False
34      else
35        if other.field.types does not fully contain field.types then
36          | flag  $\leftarrow$  False
37        end
38      end
39    end
40    for method in class do
41      if method contains type not in relation then
42        | return False
43      end
44      if other does not contain method then
45        | flag  $\leftarrow$  False
46      else
47        if other.method.types does not fully contain method.types then
48          | flag  $\leftarrow$  False
49        end
50      end
51    end
52    if flag = True then
53      | relation[other].add
54    end
55  end
56 end

```

Algorithm 2: Semantic Subtyping for SFJ Classes

Therefore, both approaches leave an expectation on the developer to ensure what they are doing is correct, hence the integration of both in SFJ is the key to overcoming these drawbacks, as one can choose which approach to use for a given task.

Furthermore, we have extended FJ with *method types*, demonstrated below to show another possible implementation of the *Polygons* Example 1.

```
class Diagonal {int diagonal((getDiagonal: void→int) shape){...}}
```

We define the method type as accepting any type and its subtypes which implement a method called *diagonal* which is a method from the type *Void* to a *Double*.

In order to type-check the value passed to such an argument, we can at compile-time build a collection of types $\{type_1, type_2, \dots\}$ which have this method. We can do this the simply iterating over the same list of classes in the program as when we were creating our subtyping relation and checking for the presence of the required method. The set of accepted types would then be the union of all their corresponding subtypes ($\llbracket type_1 \rrbracket_B \cup \llbracket type_2 \rrbracket_B \cup \dots$).

However, calculating this collection of types for each method of every class would be computationally unnecessary as only few of these would be used for method types. Therefore we only compute them on demand during type-checking when we come across such a type.

We can therefore use method types to statically include or exclude a portion of our type hierarchy. However unlike the use of interfaces such as in the suggested Java solution to the Polygons problem Example 1, the values that can be accepted by a method type do not have to be related to each other in any way in the class hierarchy. This becomes increasingly useful if we have a legacy system as we can still accept all the classes that have defined *Diagonal* methods without having to go back and add interface implementations.

4 Related Work and Conclusion

Semantic subtyping approach goes back to more than two decades ago [1,8]. Notable lines of work include: Hosoya and Pierce [13,15,14] who define XDuce, an XML-oriented language designed specifically to transform XML documents in other XML documents satisfying certain properties. Castagna *et al.* [?,5,12] extend XDuce with first-class functions and arrow types and implement it as CDuce. The starting point of their framework is a higher-order λ -calculus with pairs and projections. Muehlboeck and Tate [21] define a syntactic framework with boolean connectives which has been implemented in the Ceylon programming language [17]. Castagna *et al.* [7] define $\mathbb{C}\pi$, a variant of the asynchronous π -calculus [25], where channel types are augmented with boolean connectives. Ancona and Lagorio [2] define subtyping for infinite types coinductively by using union and object type constructors, where types are interpreted as sets of value of the language. Bonsangue *et al.* [3] study a coalgebraic approach to coinductive types and define a set-theoretic interpretation of coinductive types with union

types. Pearce [24] defines semantic subtyping for rewriting rules in the Whiley Rewrite Language and for a flow-typing calculus [23].

To conclude, in this paper we presented the design and implementation of SFJ, an extension of Featherweight Java with boolean types and semantic subtyping, which allow for both structural and nominal subtyping in FJ as well as restore standard Java constructs for example, lists and features for example, overloading which were not present in FJ, making SFJ a more complete language.

References

1. Aiken, A., Wimmers, E.L.: Type inclusion constraints and type inference. In: Proceedings of the conference on Functional Programming Languages and Computer Architecture, FPCA. pp. 31–41. ACM, New York, NY, USA (1993). <https://doi.org/10.1145/165180.165188>
2. Ancona, D., Lagorio, G.: Coinductive subtyping for abstract compilation of object-oriented languages into horn formulas. In: Proceedings of the Symposium on Games, Automata, Logic, and Formal Verification, GANDALF. EPTCS, vol. 25, pp. 214–230 (2010). <https://doi.org/10.4204/EPTCS.25.20>
3. Bonsangue, M.M., Rot, J., Ancona, D., de Boer, F.S., Rutten, J.J.M.M.: A coalgebraic foundation for coinductive union types. In: Proceedings of the International Colloquium on Automata, Languages, and Programming, ICALP. LNCS, vol. 8573, pp. 62–73. Springer (2014). https://doi.org/10.1007/978-3-662-43951-7_6
4. Boyland, J., Castagna, G.: Parasitic methods: An implementation of multi-methods for java. In: Proceedings of the Conference on Object-Oriented Programming Systems, Languages & Applications OOPSLA. pp. 66–76. ACM (1997). <https://doi.org/10.1145/263698.263721>
5. Castagna, G.: Semantic subtyping: Challenges, perspectives, and open problems. In: ICTCS. pp. 1–20 (2005)
6. Castagna, G., Frisch, A.: A gentle introduction to semantic subtyping. In: Proceedings of the Conference on Principles and Practice of Declarative Programming, PPDP. vol. 2005, pp. 198–208 (2005). <https://doi.org/10.1145/1069774.1069793>
7. Castagna, G., Nicola, R.D., Varacca, D.: Semantic subtyping for the pi-calculus. Theor. Comput. Sci. **398**(1-3), 217–242 (2008). <https://doi.org/10.1016/j.tcs.2008.01.049>
8. Damm, F.M.: Subtyping with union types, intersection types and recursive types. In: Proceedings of the International Conference on Theoretical Aspects of Computer Software, TACS. pp. 687–706. Springer-Verlag, London, UK (1994)
9. Dardha, O., Gorla, D., Varacca, D.: Semantic Subtyping for Objects and Classes. In: Proceedings of the International Conference on Formal Techniques for Distributed Systems, FMOODS/FORTE. LNCS, vol. 7892, pp. 66–82. Springer (2013). https://doi.org/10.1007/978-3-642-38592-6_6
10. Dardha, O., Gorla, D., Varacca, D.: Semantic Subtyping for Objects and Classes. Comput. J. **60**(5), 636–656 (2017). <https://doi.org/10.1093/comjnl/bxw080>
11. Frisch, A., Castagna, G., Benzaken, V.: Semantic subtyping: Dealing set-theoretically with function, union, intersection, and negation types. Journal of the ACM **55** (2008). <https://doi.org/10.1145/1391289.1391293>
12. Frisch, A., Castagna, G., Benzaken, V.: Semantic subtyping: Dealing set-theoretically with function, union, intersection, and negation types. J. ACM **55**(4), 1–64 (2008). <https://doi.org/10.1145/1391289.1391293>
13. Hosoya, H., Pierce, B.C.: Regular expression pattern matching for xml. SIGPLAN Not. **36**(3), 67–80 (2001). <https://doi.org/10.1145/373243.360209>
14. Hosoya, H., Pierce, B.C.: Xduce: A statically typed xml processing language. ACM Trans. Internet Technol. **3**(2), 117–148 (2003). <https://doi.org/10.1145/767193.767195>
15. Hosoya, H., Vouillon, J., Pierce, B.C.: Regular expression types for xml. ACM Trans. Program. Lang. Syst. **27**(1), 46–90 (2005). <https://doi.org/10.1145/1053468.1053470>

16. Igarashi, A., Pierce, B.C., Wadler, P.: Featherweight java: a minimal core calculus for java and gj. *ACM Trans. Program. Lang. Syst.* **23**(3), 396–450 (2001). <https://doi.org/10.1145/503502.503505>
17. King, G.: The Ceylon Language Specification, Version 1.3 (2016), <https://ceylon-lang.org/documentation/1.3/spec/>
18. Liskov, B.H., Wing, J.M.: A behavioral notion of subtyping. *ACM Trans. Program. Lang. Syst.* **16**(6), 1811–1841 (1994). <https://doi.org/10.1145/197320.197383>
19. Malayeri, D., Aldrich, J.: Integrating nominal and structural subtyping. In: *Proceedings of the European Conference on Object-Oriented Programming, ECOOP*. pp. 260–284. Springer-Verlag, Berlin, Heidelberg (2008). https://doi.org/10.1007/978-3-540-70592-5_12
20. Malayeri, D., Aldrich, J.: Is structural subtyping useful? an empirical study. In: *Proceedings of the European Symposium on Programming ESOP*. pp. 95–111 (2009)
21. Muehlboeck, F., Tate, R.: Empowering union and intersection types with integrated subtyping. *Proceedings of the Conference on Object-Oriented Programming Systems, Languages & Applications OOPSLA* **2**, 1–29 (2018). <https://doi.org/10.1145/3276482>
22. Parr, T.: The definitive ANTLR 4 reference. Pragmatic Bookshelf (2013)
23. Pearce, D.J.: Sound and complete flow typing with unions, intersections and negations. In: Giacobazzi, R., Berdine, J., Mastroeni, I. (eds.) *Proceedings of the International Conference on Verification, Model Checking, and Abstract Interpretation, VMCAI*. LNCS, vol. 7737, pp. 335–354. Springer (2013). https://doi.org/10.1007/978-3-642-35873-9_21
24. Pearce, D.J.: On declarative rewriting for sound and complete union, intersection and negation types. *J. Comput. Lang.* **50**, 84–101 (2019). <https://doi.org/10.1016/j.jvlc.2018.10.004>
25. Sangiorgi, D., Walker, D.: *The Pi-Calculus: A Theory of Mobile Processes*. Cambridge University Press, New York, NY, USA (2003)
26. Usov, A., Dardha, O.: SFJ: An implementation of Semantic Featherweight Java (2020), On YouTube <https://youtu.be/oTFIjm0A208> and on Dardha’s website <http://www.dcs.gla.ac.uk/~ornela/publications/SFJ.mp4>