

Disjoint Intersection Types

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Abstract

Dunfield has shown that a simply typed core calculus with intersection types and a merge operator is able to capture various programming language features. While his calculus is type-safe, it is known that it is not *coherent*: different derivations for the same expression can lead to different results. The lack of coherence is an important disadvantage for adoption of his core calculus in implementations of programming languages, as the semantics of the programming language becomes implementation-dependent.

This paper presents λ_i : a core calculus with a variant of *intersection types* and a *merge operator*. The semantics λ_i is both type-safe and coherent. Coherence is achieved by ensuring that intersection types are *disjoint*. Formally, two types are disjoint if they do not share a common supertype. **BRUNO: Abstract needs to be fixed, disjointness is no longer the absence of a common supertype!** We present a type system that prevents intersection types that are not disjoint, as well as an algorithmic specification to determine whether two types are disjoint. Moreover, we show the applicability of this calculus to express a simple, yet powerful form of dynamically composable traits, paving the way for new designs of object-oriented programming languages. **BRUNO: Drop sentence about traits and replace by other contributions?**

Categories and Subject Descriptors CR-number [subcategory]: third-level

General Terms Design, Languages, Theory

Keywords Intersection Types, Polymorphism, Type System

1. Introduction

Previous work by Dunfield [12] has shown the usefulness of type systems with intersection types and a merge operator. The presence of a merge operator in a core calculus provides significant expressiveness, allowing encodings for many other language constructs as syntactic sugar. For example single-field records are easily encoded as types with a label, and multi-field records are encoded as the concatenation of single-field records. Concatenation of records is expressed using intersection types at the type-level and the corresponding merge operator at the term level. Dunfield formalized a simply typed lambda calculus with intersection types and a merge operator. He showed how to give a semantics to the calculus by

a type-directed translation to a simply typed lambda calculus extended with pairs. The type-directed translation is elegant and type-safe.

While Dunfield's calculus is type-safe, it lacks the property of *coherence*: different derivations for the same expression can lead to different results. The lack of coherence is an important disadvantage for adoption of his core calculus in implementations of programming languages, as the semantics of the programming language becomes implementation dependent. Although Dunfield mentioned the possibility of extending the type system to allow only disjoint intersection types, he did not formalize or further pursue this approach.

This paper presents λ_i : a core calculus with a variant of *intersection types* and a *merge operator*. The semantics of λ_i is both type-safe and coherent. Coherence is achieved by ensuring that intersection types are *disjoint*. **BRUNO: introduction needs to be rewritten at least from this point!**

Given two types A and B , two types are disjoint $(A * B)^1$ if there is no type C such that both A and B are subtypes of C . Formally this definition is captured as follows:

$$A * B \equiv \neg C. A <: C \wedge B <: C$$

With this definition of disjointness we present a formal specification of a type system that prevents intersection types that are not disjoint. However, the formal definition of disjointness does not lend itself directly to an algorithmic implementation. Therefore, we also present an algorithmic specification to determine whether two types are disjoint. Moreover, this specification is shown to be sound and complete with respect to the formal definition of disjointness. We have mechanized the many of the interesting metatheoretical results using the Coq proof assistant, and the main proof of type-safety and the coherence theorem can be found in the full version of the paper².

As an application of λ_i , we show that λ_i can serve as a foundation for a trait-based [20] object-oriented language. Due to the type system of λ_i , the language supports common features of traits such as commutative composition, explicit conflict detection and resolution. In addition, our language also supports instantiating and composing traits dynamically, which cannot be achieved in many existing statically typed object-oriented languages.

In summary, the contributions of this paper are:

- **Disjoint Intersection Types:** A new form of intersection type where only disjoint types are allowed. A sound and complete algorithmic specification of disjointness (with respect to the corresponding formal definition) is presented.
- **Dynamically Composable Traits:** As an application of this work, we show how to build a trait-based object-oriented lan-

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¹The notation $A * B$ is inspired by the *separating conjunction* construct in Reynolds' separation logic [19].

²<https://github.com/zhiyuanshi/intersection/blob/master/esop-16/paper-full.pdf>

guage by leveraging the type system of λ_i . The resulting source language enjoys many features described in the original traits proposal for free.

- **Formalization of λ_i and Proof of Coherence:** An elaboration semantics of λ_i into λ -calculus is given. Type-soundness and coherence are proved and formalized. Several key theorems are mechanically formalized using the Coq theorem prover.
- **Implementation:** An implementation of an extension of λ_i , as well as encodings of the examples presented in the paper, are publicly available online³.

BRUNO: Records and record operations missing in the appendix.

2. Overview

This section introduces λ_i and its support for intersection types and the merge operator. It then discusses the issue of coherence and shows how the notion of disjoint intersection types achieve a coherent semantics.

Note that this section uses some syntactic sugar, as well as standard programming language features, to illustrate the various concepts in λ_i . Although the minimal core language that we formalize in Section 3 does not present all such features, our implementation supports them.

2.1 Intersection Types and the Merge Operator

Intersection types date back as early as Coppo *et al.*'s work [7]. Since then various researchers have studied intersection types [?], and some languages have adopted them in one form or another[?]. **BRUNO:** Reviewer asked for more references here.

Intersection Types. The intersection of type A and B (denoted as $A \& B$ in λ_i) contains exactly those values which can be used as either values of type A or of type B. For instance, consider the following program in λ_i :

```
let x : Int & Bool = ... in -- definition omitted
let succ (y : Int) : Int = y+1 in
let not (y : Bool) : Bool = if y then False else True in
(succ x, not x)
```

If a value x has type $\text{Int} \& \text{Bool}$ then x can be used as an integer and as a boolean. Therefore, x can be used as an argument to any function that takes an integer as an argument, and any function that take a boolean as an argument. In the program above the functions `succ` and `not` are the simple functions on integers and characters, respectively. Passing x as an argument to either one (or both) of the functions is valid.

Merge Operator. In the previous program we deliberately did not show how to introduce values of an intersection type. There are many variants of intersection types in the literature. Our work follows a particular formulation, where intersection types are introduced by a *merge operator*. **BRUNO:** Perhaps mention other works with the merge operator, including lambda& As Dunfield [12] has argued a merge operator adds considerable expressiveness to a calculus. The merge operator allows two values to be merged in a single intersection type. In λ_i (following Dunfield's notation), the merge of two values v_1 and v_2 is denoted as v_1, v_2 . For example, an implementation of x is constructed in λ_i as follows:

```
let x : Int & Boolean = 1, True in ...
```

Merge Operator and Pairs. The merge operator is similar to the introduction construct on pairs. An analogous implementation of x with pairs would be:

```
let xPair : (Int, Bool) = (1, True) in ...
```

The significant difference between intersection types with a merge operator and pairs is in the elimination construct. With pairs there are explicit eliminators (`fst` and `snd`). These eliminators must be used to extract the components of the right type. For example, in order to use `succ` and `not` with pairs, we would need to write a program such as:

```
(succ (fst xPair), not (snd xPair))
```

In contrast the elimination of intersection types is done implicitly, by following a type-directed process. For example, when a value of type `Int` is needed, but an intersection of type `Int & Bool` is found, the compiler generates code that uses `fst` to extract the corresponding value at runtime.

2.2 (In)Coherence

Coherence is a desirable property for the semantics of a programming language. A semantics is said to be coherent if any *valid program* has exactly one meaning [17] (that is, the semantics is not ambiguous). In contrast a semantics is said to be *incoherent* if there are multiple possible meanings for the same valid program.

Incoherence in Dunfield's calculus A problem with Dunfield's calculus [12] is that it is incoherent. Unfortunately the implicit nature of elimination for intersection types built with a merge operator can lead to incoherence. The merge operator combines two terms, of type A and B respectively, to form a term of type $A \& B$. For example, `1, True` is of type $\text{Int} \& \text{Bool}$. In this case, no matter if `1, True` is used as `Int` or `Bool`, the result of evaluation is always clear. However, with overlapping types, it is not straightforward anymore to see the intended result. For example, what should be the result of the following program, which asks for an integer (using a type annotation) out of a merge of two integers:

```
(1, 2) : Int
```

Should the result be 1 or 2?

Dunfield's calculus [12] accepts the program above, and it allows that program to result in 1 or 2. In other words the results of the program are incoherent. **BRUNO:** rephrase better?

Getting Around Incoherence In a real implementation of Dunfield calculus a choice has to be made on which value to compute. For example, one potential option is to always take the left-most value matching the type in the merge. Similarly, one could always take the right-most value matching the type in the merge. Either way, the meaning of a program will depend on a biased implementation choice, which is clearly unsatisfying from the theoretical point of view. Dunfield suggests some other possibilities, such as the possibility of restricting typing of merges so that a merge has type A only if exactly one branch has type A. He also suggested another possibility, which is to allow only for *disjoint* types in an intersection. This is the starting point for us and the approach that we will investigate in this paper.

2.3 Disjoint Intersection Types and their Challenges

λ_i requires that the two types in an intersection to be *disjoint*. Informally saying that two types are disjoint means that the set of values of both types are disjoint. Disjoint intersection types are potentially useful for coherence, since they can rule out ambiguity when looking up a value of a certain type in an intersection. However there are several issues that need to be addressed first in order to design a calculus with disjoint intersection types and that ensures coherence. The key issues and the solutions provided by our work are discussed next. We emphasize that although Dunfield has mentioned disjointness as an option to restore coherence, he has not studied the approach further or addressed the issues discussed next.

³ <https://github.com/hkuplg/fcore/tree/develop/examples/traits>

Simple disjoint intersection types Looking back at the expression 1, 2 in Section 2.2, we can see that the reason for incoherence is that there are multiple, overlapping, integers in the merge. Generally speaking, if both terms can be assigned some type C , both of them can be chosen as the meaning of the merge, which leads to multiple meanings of a term. A natural option is to try to forbid such overlapping values of the same type in a merge. Thus, for atomic types such as `Int` and `Bool`, it is easy to see that disjointness holds when the two types are different. Intersections such as `Int & Bool` and `String & Bool` are clearly disjoint.

Disjointness of non-atomic types While it is easy to see how disjointness works for atomic types, it is more challenging to see what disjointness mean for non-atomic types. For example, consider the following intersection types of functions:

1. $(\text{Int} \rightarrow \text{Int}) \& (\text{String} \rightarrow \text{String})$
2. $(\text{String} \rightarrow \text{Int}) \& (\text{String} \rightarrow \text{String})$
3. $(\text{Int} \rightarrow \text{String}) \& (\text{String} \rightarrow \text{String})$

Which of those intersection types are disjoint? It seems reasonable to expect that the first intersection type is disjoint: both the domain and codomain of the two functions in the intersection are different. However, it is less clear whether the two other intersection types are disjoint or not. This paper proposes the following rule for determining the disjointness of two function types:

$$\frac{\vdash A_2 *_i B_2}{\vdash A_1 \rightarrow A_2 *_i B_1 \rightarrow B_2} \text{DIS-FUN}$$

Here $*_i$ denotes disjointness. According to the rule the first two intersection types are disjoint, whereas the last one is not. This rule is justified in Section ??**BRUNO: Should we stop here; or briefly argue about some justification**

Formalizing disjointness Another challenge is how to formalize the notion of disjointness? So far all discussion about disjointness has been based on an informal understanding of what disjointness means. Clearly a formal definition of disjointness is desirable to design a calculus with disjoint intersection types. As we shall see the particular notion of disjointness can be quite sensitive to the language features that are allowed in a language.

A first attempt at a definition for disjointness is to require that, given two types A and B , both types are not subtypes of each other. Thus, denoting disjointness as $A * B$, we would have:

$$A * B \equiv A \not\prec B \text{ and } B \not\prec A$$

At first sight this seems a reasonable definition and it does prevent merges such as 1, 2. However some moments of thought are enough to realize that such definition does not ensure disjointness. For example, consider the following merge:

$(1, 'c') \text{ , , } (2, \text{True})$

This merge has two components which are also intersection types. The first component $(1, 'c')$ has type `Int&Char`, whereas the second component $(2, \text{True})$ has type `Int&Bool`. Clearly,

$$\text{Int}\&\text{Char} \not\prec \text{Int}\&\text{Bool} \wedge \text{Int}\&\text{Bool} \not\prec \text{Int}\&\text{Char}$$

Nevertheless the following program still leads to incoherence:

`succ ((1, 'c'), (2, True))`

as both 2 or 3 are possible outcomes of the program. Although this attempt to define disjointness failed, it did bring us some additional insight: although the types of the two components of the merge are not subtypes of each other, they share some types in common.

In order for two types to be truly disjoint, they must not have any subcomponents sharing the same type. In a simply typed calculus

with intersection types (and without a \top type) this can be ensured by requiring the two types not to share a common supertype:

Definition 1 (Simple disjointness). Given two types A and B , two types are disjoint (written $A * B$) if there is no type C such that both A and B are subtypes of C :

$$A * B \equiv \nexists C. A <: C \text{ and } B <: C$$

This definition of disjointness prevents the problematic $(1, 'c') \text{ , , } (2, \text{True})$ merge. Since `Int` is a common supertype of both `Int&Char` and `Int&Bool`, those two types are not disjoint, according to this simple notion of disjointness.

The simple definition of disjointness is the basis for the first calculus presented in this paper: a simply typed lambda calculus with intersection (but without a \top type). This variant of λ_i is useful to study many important issues arising from disjoint intersections, without the additional complications of \top .

Disjointness in the presence of \top types In the presence of a \top type the simple definition of disjointness is useless. In that case there *always* exists a common supertype (for example, the \top type). So adding a \top type requires some adaptations on the notion of disjointness. This work studies two additional variants of λ_i with \top types. In both variants the definition of disjointness is revised as follows:

Definition 2 (Disjointness with \top). Given two types A and B , two types are disjoint (written $A * B$) if the following two conditions are met:

1. $\neg A_\top$ and $\neg B_\top$
2. $\forall C. \text{ if } A <: C \text{ and } B <: C \text{ then } C_\top$

In this definition the idea is to allow A and B to share some common supertypes. Instead of requiring that two types do not have any common supertype, we require that the only supertypes are *top-like*. The unary relation A_\top denotes such top-like types. As shown in this paper allowing such supertypes does not cause incoherence.**BRUNO: Explanation probably needs to be expanded**

λ_i 's type system only accepts programs that use disjoint intersection types. As shown in Section 4 disjoint intersection types will play a crucial rule in guaranteeing that the semantics is coherent.

Is disjointness sufficient to ensure coherence? A final question is whether disjoint intersection types are sufficient to ensure coherence. Consider the following example:

`(succ, not) (3, True)`

Here there are two merges, with the first merge being applied to the second. The first merge contains two functions (`succ` and `not`). The second merge contains two values that can serve as input to the functions. The two merges are disjoint. However what should be the result of this program? Should it be 4 or `False`?

At first this program appears to lead to incoherence, even though it only uses disjoint merges. However, a closer look reveals that there are two possible types for this program: `Int` or `Bool`. Once the type of the program is fixed, there is only one possible result: if the type is `Int` the result of the program is 4; if the type is `Bool` then the result of the program is `False`. Like other programming language features (for example type classes `[]`), types play a fundamental role in determining the result of a program, and the semantics of the language is not independent from types.

Disjointness is indeed sufficient to ensure coherence. The key point is that given a program *and its type* there is always a unique result for that program. However, for certain programs type annotations are necessary to rule out *type ambiguity*. Similar type ambiguity issues arise in other type-directed mechanisms such as type-classes `[]`.

Types	A, B, C	$::=$	Int $A \rightarrow B$ $A \& B$ \top
Terms	e	$::=$	i x $\lambda(x:A). e$ $e_1 e_2$ e_1, e_2 \top
Contexts	Γ	$::=$	$\cdot \mid \Gamma, x:A$

Figure 1. λ_i syntax.

In our implementation, which uses bi-directional type-checking techniques [], the ambiguity problem is solved by annotating the term being applied. For example:

$((\text{succ}, \text{not}) : \text{Int} \rightarrow \text{Int}) (3, \text{True})$

is a valid program and results in 4.

3. The λ_i Calculus

This section presents the syntax, subtyping, typing, as well as the (incoherent) semantics of λ_i : a calculus with intersection types and a merge operator. This calculus is inspired by Dunfield’s calculus [12]. However our calculus does not consider union types, and due to the fact that we are interested only in disjoint intersections, it also has a few less typing rules than in Dunfield’s calculus. **BRUNO: rephrase next** The differences are that, in Dunfield’s language, the coercions are source language terms and that function application allows the expression denoting the function to have an intersection type. Sections 4 and 5 will present the more fundamental contributions of this paper by showing other necessary changes for supporting disjoint intersection types and ensuring coherence.

3.1 Syntax

Figure 1 shows the syntax. The differences to the λ -calculus, highlighted in gray, are intersection types $A \& B$ at the type-level and the “merges” e_1, e_2 at the term level.

Types. Metavariables A, B range over types. Types include function types $A \rightarrow B$. $A \& B$ denotes the intersection of types A and B . We also include \top and integer types Int .

Terms. Metavariables e range over terms. Terms include standard constructs: variables x ; abstraction of terms over variables of a given type $\lambda(x : A). e$; and application of terms e_1 to terms e_2 , written $e_1 e_2$. The expression e_1, e_2 is the *merge* of two terms e_1 and e_2 . Merges of terms correspond to intersections of types $A \& B$. The term \top corresponds to the only inhabitant of the \top type. In addition, we also include integer literals i .

Contexts. Typing contexts Γ track bound variables x with their type A .

In order to focus on the key features that make this language interesting, we do not include other forms such as type constants and fixpoints here. However they can be included in the formalization in standard ways and we are using them in discussions and examples. The formalization of nonessential features such as records and record operations can be found in the full version of the paper.

$A <: B \hookrightarrow E$	
$\frac{}{\alpha <: \alpha \hookrightarrow \lambda(x: \alpha). x}$	SUB-VAR
$\frac{}{\text{Int} <: \text{Int} \hookrightarrow \lambda(x: \text{Int}). x}$	SUB-INT
$\frac{B_1 <: A_1 \hookrightarrow E_1 \quad A_2 <: B_2 \hookrightarrow E_2}{A_1 \rightarrow A_2 <: B_1 \rightarrow B_2 \hookrightarrow \lambda(f: A_1 \rightarrow A_2). \lambda(x: B_1). E_2 (f (E_1 x))}$	SUB-FUN
$\frac{A_1 <: A_2 \hookrightarrow E_1 \quad A_1 <: A_3 \hookrightarrow E_2}{A_1 <: A_2 \& A_3 \hookrightarrow \lambda(x: A_1). (E_1 x, E_2 x)}$	SUB-INTER
$\frac{A_1 <: A_3 \hookrightarrow E}{A_1 \& A_2 <: A_3 \hookrightarrow \lambda(x: A_1 \& A_2). E (\text{proj}_1 x)}$	SUB-INTER-1
$\frac{A_2 <: A_3 \hookrightarrow E}{A_1 \& A_2 <: A_3 \hookrightarrow \lambda(x: A_1 \& A_2). E (\text{proj}_2 x)}$	SUB-INTER-2
$\frac{}{A <: \top \hookrightarrow \lambda(_ : A). ()}$	SUB-TOP
$\Gamma \vdash A$	
$\frac{}{\Gamma \vdash \text{Int}}$	F-WF-INT
$\frac{\Gamma \vdash A \quad \Gamma \vdash B}{\Gamma \vdash A \rightarrow B}$	F-WF-FUN
$\frac{\Gamma \vdash A \quad \Gamma \vdash B}{\Gamma \vdash A \& B}$	F-WF-INTER
$\frac{}{\Gamma \vdash \top}$	F-WF-TOP
$\Gamma \vdash e : A \hookrightarrow E$	
$\frac{x:A \in \Gamma}{\Gamma \vdash x : A \hookrightarrow x}$	F-TY-VAR
$\frac{}{\Gamma \vdash i : \text{Int}}$	F-TY-INT
$\frac{\Gamma \vdash A \quad \Gamma, x:A \vdash e : B \hookrightarrow E}{\Gamma \vdash \lambda(x:A). e : A \rightarrow B \hookrightarrow \lambda(x: A). E}$	F-TY-LAM
$\frac{\Gamma \vdash e_1 : A_1 \hookrightarrow E_1 \quad \Gamma \vdash e_2 : A_2 \hookrightarrow E_2 \quad A_3 <: A_1 \hookrightarrow E}{\Gamma \vdash e_1 e_2 : A_2 \hookrightarrow E_1 (E E_2)}$	F-TY-APP
$\frac{\Gamma \vdash e_1 : A \hookrightarrow E_1 \quad \Gamma \vdash e_2 : B \hookrightarrow E_2}{\Gamma \vdash e_1, e_2 : A \& B \hookrightarrow (E_1, E_2)}$	F-TY-MERGE
$\frac{}{\Gamma \vdash \top : \top \hookrightarrow ()}$	F-TY-TOP
$\frac{}{\Gamma \vdash \top : \top \hookrightarrow ()}$	F-TY-TOP

Figure 2. Declarative type system of λ_i .

3.2 Subtyping

The subtyping rules of the form $A <: B$ are shown in the top part of Figure 2. At the moment, the reader is advised to ignore the gray-shaded part in the rules, which will be explained later. The rule (SUB-FUN) says that a function is contravariant in its parameter type and covariant in its return type. The three rules dealing with intersection types are just what one would expect when interpreting types as sets. Under this interpretation, for example, the rule (SUB-INTER) says that if A_1 is both the subset of A_2 and the subset of A_3 , then A_1 is also the subset of the intersection of A_2 and A_3 .

Metatheory. As other sane subtyping relations, we can show that subtyping defined by $<:$ is also reflexive and transitive.

Lemma 1 (Subtyping is reflexive). *For all type A , $A <: A$.*

Lemma 2 (Subtyping is transitive). *If $A_1 <: A_2$ and $A_2 <: A_3$, then $A_1 <: A_3$.*

For the corresponding mechanized proofs in Coq, we refer the reader to the repository associated with the paper⁴.

3.3 Declarative Type System

The well-formedness rules are shown in the middle part of Figure 2. In addition to the standard rules, (F-WF-INTER) is also not surprising. The typing rules are shown in the bottom part of the figure. The typing judgment is of the form:

$$\Gamma \vdash e : A$$

It reads: “in the typing context Γ , the term e is of type A ”. The standard rules are those for variables (F-TY-VAR) and lambda abstractions (F-TY-LAM). (F-TY-MERGE) means that a merge e_1, e_2 , is assigned an intersection type composed of the resulting types of e_1 and e_2 .

Differences to Dunfield’s Calculus

3.4 Algorithmic Type System

Introduce the bi-directional type system here?

3.5 Semantics

We define the dynamic semantics of the call-by-value λ_i by means of a type-directed translation to an extension of λ -calculus with pairs.

Target Language. The syntax and typing of our target language is unsurprising. The syntax of the target language is shown in Figure 3. The highlighted part shows its difference with the λ -calculus. The typing rules can be found in the extended version of the paper.

Key Idea of the Translation. This translation turns merges into usual pairs, similar to Dunfield’s elaboration approach [12]. For example,

$$1, \text{"one"}$$

becomes $(1, \text{"one"})$. In usage, the pair will be coerced according to type information. For example, consider the function application:

$$(\lambda(x:\text{String}).x) (1, \text{"one"})$$

This expression will be translated to

$$(\lambda(x:\text{String}).x) ((\lambda(x:(\text{Int}, \text{String})).\text{proj}_2 x) (1, \text{"one"}))$$

The coercion in this case is $(\lambda(x : (\text{Int}, \text{String})).\text{proj}_2 x)$. It extracts the second item from the pair, since the function expects a String but the translated argument is of type $(\text{Int}, \text{String})$.

⁴<https://github.com/zhiyuanshi/intersection/tree/master/esop-16>

Types	T	$::=$	Int $()$ $T_1 \rightarrow T_2$ (T_1, T_2)
Terms	E	$::=$	x i $()$ $\lambda(x:T). E$ $E_1 E_2$ (E_1, E_2) $\text{proj}_k E \quad k \in \{1, 2\}$
Contexts	G	$::=$	$\cdot \mid G, x:T$

Figure 3. Target language syntax.

$$|A| = T$$

$$\begin{aligned}
|\text{Int}| &= \text{Int} \\
|A_1 \rightarrow A_2| &= |A_1| \rightarrow |A_2| \\
|A_1 \&A_2| &= (|A_1|, |A_2|) \\
|T| &= ()
\end{aligned}$$

$$|\Gamma| = G$$

$$\begin{aligned}
|\cdot| &= \cdot \\
|\Gamma, \alpha:A| &= |\Gamma|, \alpha:|A|
\end{aligned}$$

Figure 4. Type and context translation.

Type and Context Translation. Figure 4 defines the type translation function $|\cdot|$ from λ_i types A to target language types T . The notation $|\cdot|$ is also overloaded for context translation from λ_i contexts Γ to target language contexts G .

Coercive subtyping. The judgment

$$A_1 <: A_2 \hookrightarrow E$$

extends the subtyping judgment in Figure 2 with a coercion on the right hand side of \hookrightarrow . A coercion E is just an term in the target language and is ensured to have type $|A_1| \rightarrow |A_2|$ (by Lemma 3). For example,

$$\text{Int}\&\text{Bool} <: \text{Bool} \hookrightarrow \lambda(x:|\text{Int}\&\text{Bool}|).\text{proj}_2 x$$

generates a coercion function with type: $\text{Int}\&\text{Bool} \rightarrow \text{Bool}$.

In (SUB-FUN), we elaborate the subtyping of parameter and return types by η -expanding f to $\lambda(x : |A_3|). f \ x$, applying E_1 to the argument and E_2 to the result. Rules (SUB-INTER-1), (SUB-INTER-2), and (SUB-INTER) elaborate intersection types. (SUB-INTER) uses both coercions to form a pair. Rules (SUB-INTER-1) and (SUB-INTER-2) reuse the coercion from the premises and create new ones that cater to the changes of the argument type in the conclusions. Note that the two rules are overlapping and hence a program can be elaborated differently, depending on which rule is used. Finally, all rules produce type-correct coercions:

Lemma 3 (Subtyping rules produce type-correct coercions). *If $A_1 <: A_2 \hookrightarrow E$, then $\cdot \vdash E : |A_1| \rightarrow |A_2|$.*

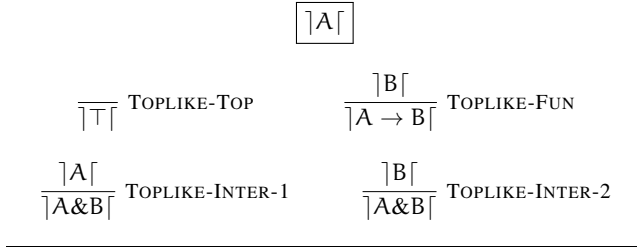


Figure 5. Top-like types.

Proof. By a straightforward induction on the derivation⁵. \square

The translation judgment. The translation judgment $\Gamma \vdash e : A \hookrightarrow E$ extends the typing judgment with an elaborated term on the right hand side of \hookrightarrow . The translation ensures that E has type \boxed{A} . In λ_i , one may pass more information to a function than what is required; but not in ordinary λ -calculus. To account for this difference, in (F-TY-APP), the coercion E from the subtyping relation is applied to the argument. (F-TY-MERGE) straightforwardly translates merges into pairs.

The type-directed translation is type-safe. This property is captured by the following two theorems.

Theorem 1 (Type preservation). *If $\Gamma \vdash e : A \hookrightarrow E$, then $\boxed{\Gamma} \vdash E : \boxed{A}$.*

Proof. (Sketch) By structural induction on the term and the corresponding inference rule. \square

Theorem 2 (Type safety). *If e is a well-typed λ_i term, then e evaluates to some λ -calculus value v .*

Proof. Since we define the dynamic semantics of λ_i in terms of the composition of the type-directed translation and the dynamic semantics of λ -calculus, type safety follows immediately. \square

4. Disjointness and Coherence

Although the system shown in the previous section is type-safe, it is not coherent, in the sense that one source program can be elaborated into two different target programs. This section shows how to modify it so that it guarantees coherence as well as type soundness. The result is a calculus named λ_i . The key aspect is the notion of disjoint intersection.

4.1 Disjointness

Throughout the paper we already presented an intuitive definition for disjointness. Before we discuss that definition, let us introduce first the notion of a top-like type

Definition 3 (Top-like types). One type A is a top-like type, denoted as \boxed{A} , if it has the form $A_k \rightarrow \top$, where $k \in 0, 1, \dots$. That is, any type with arity k can be a top-like type, as long as \top is the result type.

Thus a top-like type is a unary relation at the type level, which can be formalized according to 5. Now, we recall the definition of disjoint types

Definition 4 (Disjoint types). Two types A and B are said to be disjoint (written $\vdash A * B$) if they do not share a common supertype

- excluding top-like types. That is, for all type C such that $A <: C$ and $B <: C$, then \boxed{C} must hold.

$$\vdash A * B \equiv \forall C. A <: C \wedge B <: C \Rightarrow \boxed{C}$$

For example, `Int` and `Char` are disjoint, if their only common supertype is \top . On the other hand, `Int` is not disjoint with itself, because `Int <: Int`. This implies that disjointness is not reflexive as subtyping is. Two types with different “shapes” are always disjoint, unless one of them is an intersection type. For example, a function type and an intersection type may not be disjoint. Consider:

`Int \rightarrow Int` and `(Int \rightarrow Int)&(String \rightarrow String)`

Those two types are not disjoint since `Int \rightarrow Int` is their common supertype. Also, `Int \rightarrow Char` and `Int \rightarrow String` are disjoint, since their supertypes are all types with the form $A \rightarrow \top$ (where A contains `Int`, i.e. `Int`, `Int&Char`) and \top .

JOAO: do we want to allow this? `f: String \rightarrow Int`
`g: String \rightarrow T`
`($\lambda. h : \text{String} \rightarrow T. h \text{ ""}$)(f, g)`

At last, take as an example $(\top \& \top)$. In a pure language (i.e. no side-effects), this type can be safely allowed since both components of the merge will evaluate to the same value. However, in an effectful language, the evaluation of either the right or left component might lead to distinct results. Following the same reasoning, we might want to allow or restrict, for instance `String \rightarrow Int&String \rightarrow \top` ,

4.2 Typing

Figure 6 shows modifications to Figure 2 in order to support disjoint intersection types. Only new rules or rules that different are shown. Importantly, the disjointness judgment appears in the well-formedness rule for intersection types and the typing rule for merges.

Well-formedness. We require that the two types of an intersection must be disjoint. Under the new rules, intersection types such as `Int&Int` are no longer well-formed because the two types are not disjoint.

Metatheory. Since in this section we only restrict the type system in the previous section, it is easy to see that type preservation and type-safety still holds.

4.3 Subtyping

The subtyping rules need some adjustment. An important problem with the subtyping rules in Figure 2 is that all three rules dealing with intersection types ((SUB-INTER-1) and (SUB-INTER-2) and (SUB-INTER)) overlap. Unfortunately, this means that different coercions may be given when checking the subtyping between two types, depending on which derivation is chosen. This is the ultimate reason for incoherence. There are two important types of overlap:

1. The left decomposition rules for intersections ((SUB-INTER-1) and (SUB-INTER-2)) overlap with each other.
2. The left decomposition rules for intersections ((SUB-INTER-1) and (SUB-INTER-2)) overlap with the right decomposition rules for intersections (SUB-INTER).

Fortunately, disjoint intersections (which are enforced by well-formedness) deal with problem 1): only one of the two left decomposition rules can be chosen for a disjoint intersection type. Since the two types in the intersection are disjoint, it is impossible that both of the preconditions of the left decompositions are satisfied at the same time. More formally, with disjoint intersections, we have the following theorem:

⁵The proofs of major lemmata and theorems can be found in the full version of the paper. BRUNO: where??

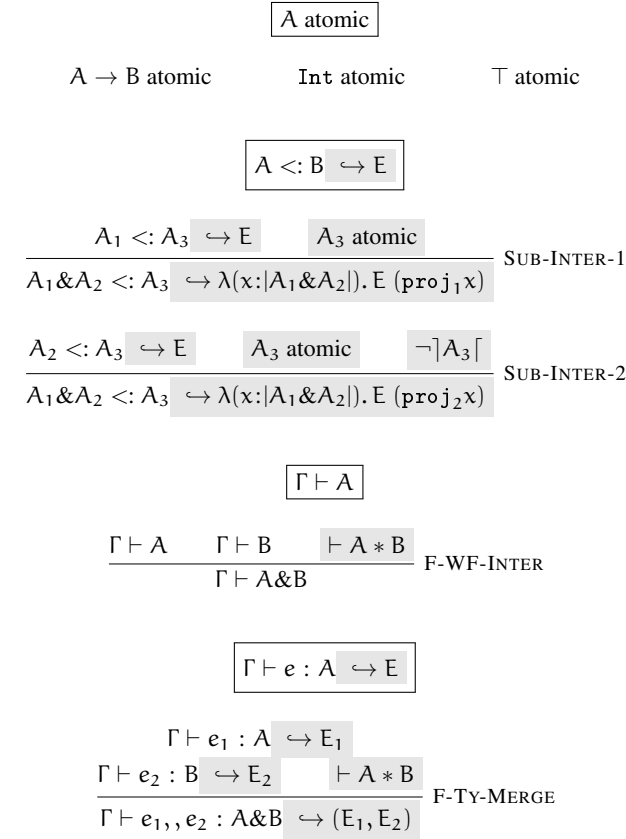


Figure 6. Affected rules.

Lemma 4 (Unique subtype contributor). *If $A_1 \& A_2 <: B$, where $A_1 \& A_2$ and B are well-formed types, then it is not possible that the following holds at the same time:*

1. $A_1 <: B$
2. $A_2 <: B$

Unfortunately, disjoint intersections alone are insufficient to deal with problem 2). In order to deal with problem 2), we introduce a distinction between types, and atomic types.

Atomic Types. Atomic types are just those which are not intersection types, and are asserted by the judgment

$A \text{ atomic}$

Since types in λ_i are simple, the only atomic types are the function type and integers. But in richer systems, it can also include, for example, record types. In the left decomposition rules for intersections we introduce a requirement that A_3 is atomic. The consequence of this requirement is that when A_3 is an intersection type, then the only rule that can be applied is (SUB-INTER). With the atomic constraint, one can guarantee that at any moment during the derivation of a subtyping relation, at most one rule can be used. Consequently, the coercion of a subtyping relation $A <: B$ is uniquely determined. This fact is captured by the following lemma:

Lemma 5 (Unique coercion). *If $A <: B \hookrightarrow E_1$ and $A <: B \hookrightarrow E_2$, where A and B are well-formed types, then $E_1 \equiv E_2$.*

No Loss of Expressiveness. Interestingly, our restrictions on subtyping do not sacrifice the expressiveness of subtyping since we have the following two theorems:

Theorem 3. *If $A_1 <: A_3$, then $A_1 \& A_2 <: A_3$.*

Theorem 4. *If $A_2 <: A_3$, then $A_1 \& A_2 <: A_3$.*

The interpretation of the two theorems is that: even though the premise is made stricter by the atomic condition, we can still derive every subtyping relation which is valid in the unrestricted system.

4.4 Coherence of the Elaboration

Combining the previous results, we are able to show the central theorem:

Theorem 5 (Unique elaboration). *If $\Gamma \vdash e : A_1 \hookrightarrow E_1$ and $\Gamma \vdash e : A_2 \hookrightarrow E_2$, then $E_1 \equiv E_2$. (“ \equiv ” means syntactical equality, up to α -equality.)*

Proof. Note that the typing rules are already syntax-directed but the case of (F-TY-APP) (copied below) still needs special attention since we need to show that the generated coercion E is unique.

$$\frac{\Gamma \vdash e_1 : A_1 \rightarrow A_2 \hookrightarrow E_1 \quad \Gamma \vdash e_2 : A_3 \hookrightarrow E_2 \quad A_3 <: A_1 \hookrightarrow E}{\Gamma \vdash e_1 e_2 : A_2 \hookrightarrow E_1 (E E_2)} \text{ F-TY-APP}$$

Luckily we know that typing judgments give well-formed types, and thus $\Gamma \vdash A_1$ and $\Gamma \vdash A_3$. Therefore we are able to apply Lemma 5 and conclude that E is unique. \square

5. Algorithmic Disjointness

Section 4 presented a type system with disjoint intersection types that is both type-safe and coherent. Unfortunately the type system is not algorithmic because the specification of disjointness does not lend itself to an implementation directly. This is a problem, because we need an algorithm for checking whether two types are disjoint or not in order to implement the type-system.

This section presents the set of rules for determining whether two types are disjoint. The set of rules is algorithmic and an implementation is easily derived from them. Therefore we solve the problem of finding an algorithm to compute disjointness. The derived set of rules for disjointness is proved to be sound and complete with respect to the definition of disjointness in Section 4.

5.1 Algorithmic Rules

The rules for the disjointness judgment are shown in Figure 8, which consists of two judgments.

Main Judgment. The judgment $\vdash A *_i B$ says two types A and B are disjoint.

The rules dealing with intersection types ((DIS-INTER-1) and (DIS-INTER-2)) are quite intuitive. The intuition is that if two types A and B are disjoint to some type C , then their intersection ($A \& B$) is also clearly disjoint to C . The rules capture this intuition by inductively distributing the relation itself over the intersection constructor ($\&$). Although those two rules overlap, the order of applying them in an implementation does not matter as applying either of them will eventually leads to the same conclusion, that is, if two types are disjoint or not.

The rule for functions (DIS-FUN) is more interesting. It says that two function types are disjoint if and only if their return types are disjoint (regardless of their parameter types!). At first this rule may look surprising because the parameter types play no role in

$$\begin{array}{c}
\boxed{\vdash A *_i B} \\
\\
\frac{\vdash A_2 *_i B_2}{\vdash A_1 \rightarrow A_2 *_i B_1 \rightarrow B_2} \text{DIS-FUN} \\
\\
\frac{\vdash A_1 *_i B \quad \vdash A_2 *_i B}{\vdash A_1 \& A_2 *_i B} \text{DIS-INTER-1} \\
\\
\frac{\vdash A *_i B_1 \quad \vdash A *_i B_2}{\vdash A *_i B_1 \& B_2} \text{DIS-INTER-2} \quad \frac{A *_ax B}{\vdash A *_i B} \text{DIS-AXIOM} \\
\\
\boxed{A *_ax B} \\
\\
\text{Int} *_ax A \rightarrow B \text{DISAX-INT-FUN} \quad A *_ax \top \text{DISAX-TOP} \\
\\
\frac{B *_ax A}{A *_ax B} \text{DISAX-SYM}
\end{array}$$

Figure 7. Algorithmic Disjointness.

the definition of disjointness. To see the reason for this consider the two function types:

$$\text{Int} \rightarrow \text{String} \quad \text{Bool} \rightarrow \text{String}$$

Even though their parameter types are disjoint, we are still able to think of a type which is a supertype for both of them. For example, $\text{Int} \& \text{Bool} \rightarrow \text{String}$. Therefore, two function types with the same return type are not disjoint. Essentially, due to the contravariance of function types, functions of the form $A \rightarrow C$ and $B \rightarrow C$ always have a common supertype (for example $A \& B \rightarrow C$). The lesson from this example is that the parameter types of two function types do not have any influence in determining whether those two function types are disjoint or not: only the return types matter.

Axioms. Up till now, the rules of $\vdash A *_i B$ have only taken care of two types with the same language constructs. But how can be the fact that Int and $\text{Int} \rightarrow \text{Int}$ are disjoint be decided? That is exactly the place where the judgment $A *_ax B$ comes in handy. It provides the axioms for disjointness. What is captured by the set of rules is that $A *_ax B$ holds for all two types of different constructs unless any of them is an intersection type.

5.2 Metatheory

The following two theorems together say that the algorithmic disjointness judgment and the definition of disjointness are “equivalent”. For detailed proofs, we refer to the Coq code in our repository.

Theorem 6 (Soundness of algorithmic disjointness). *For any two types A and B , $\vdash A *_i B$ implies $A *_ax B$.*

Proof. By induction on the derivation of $\vdash A *_i B$. \square

Theorem 7 (Completeness of algorithmic disjointness). *For any two types A , B , $A *_ax B$ implies $\vdash A *_i B$.*

Proof. By a case analysis on the shape of A and B . \square

$$\begin{array}{c}
\boxed{\vdash A *_i B} \\
\\
\frac{\vdash A_2 *_i B_2 \quad \neg \vdash A_2 \mid \neg \vdash B_2 \mid}{\vdash A_1 \rightarrow A_2 *_i B_1 \rightarrow B_2} \text{DIS-FUN} \\
\\
\frac{\vdash A_2 *_i B_2 \quad \neg \vdash A_2 \mid \mid B_2 \mid \quad A_1 *_i B_1}{\vdash A_1 \rightarrow A_2 *_i B_1 \rightarrow B_2} \text{DIS-FUN} \\
\\
\frac{\vdash A_2 *_i B_2 \quad \mid A_2 \mid \neg \mid B_2 \mid \quad A_1 *_i B_1}{\vdash A_1 \rightarrow A_2 *_i B_1 \rightarrow B_2} \text{DIS-FUN} \\
\\
\frac{\vdash A_1 *_i B \quad \vdash A_2 *_i B}{\vdash A_1 \& A_2 *_i B} \text{DIS-INTER-1} \\
\\
\frac{\vdash A *_i B_1 \quad \vdash A *_i B_2}{\vdash A *_i B_1 \& B_2} \text{DIS-INTER-2} \\
\\
\frac{A *_ax B}{\vdash A *_i B} \text{DIS-AXIOM}
\end{array}$$

$$\begin{array}{c}
\boxed{A *_ax B} \\
\\
\text{Int} *_ax A \rightarrow B \text{DISAX-INT-FUN} \quad \text{Int} *_ax \top \text{DISAX-TOP} \\
\\
A \rightarrow B *_ax \top \text{DISAX-TOP} \quad \frac{B *_ax A}{A *_ax B} \text{DISAX-SYM}
\end{array}$$

Figure 8. Impure Algorithmic Disjointness.

6. Related Work

Coherence. Reynolds invented Forsythe [18] in the 1980s. Our merge operator is analogous to his operator p_1, p_2 . Forsythe has a coherent semantics. The result was proved formally by Reynolds [17] in a lambda calculus with intersection types and a merge operator. However the way coherence is ensured is not general enough. He has four different typing rules for the merge operator, each accounting for various possibilities of what the types of the first and second components are. In some cases the meaning of the second component takes precedence (that is, is biased) over the first component. The set of rules is restrictive and it forbids, for instance, the merge of two functions (even when they are provably disjoint). Therefore, Forsythe treatment of coherence is rather ad-hoc. In contrast, disjointness in λ_i has a simple, well-defined specification and it is quite flexible.

Pierce [16] made a comprehensive review of coherence, especially on Curien and Ghelli [8] and Reynolds’ methods of proving coherence; but he was not able to prove coherence for his F_{\wedge} calculus. He introduced a primitive `glue` function as a language extension which corresponds to our merge operator. However, in his system users can “glue” two arbitrary values, which can lead to incoherence.

Our work is largely inspired by Dunfield [12]. He described a similar approach to ours: compiling a system with intersection types and a merge operator into ordinary λ -calculus terms with pairs. One major difference is that our system does not include unions. As acknowledged by Dunfield, his calculus lacks of coherence. He discusses the issue of coherence throughout his paper, mentioning biased choice as an option (albeit a rather unsatisfying one). He also mentioned that the notion of disjoint intersection

could be a good way to address the problem, but he did not pursue this option in his work.

Recently, Castagna *et al.* [5] studied an very interesting and coherent calculus that has polymorphism and set-theoretic type connectives (such as intersections, unions, and negations). Unfortunately their calculus does not include a merge operator like ours, which is our major source of difficulty for achieving coherence.

Going in the direction of higher kinds, Compagnoni and Pierce [6] added intersection types to System F_ω and used the new calculus, $F_{\omega, \cap}$, to model multiple inheritance. In their system, types include the construct of intersection of types of the same kind K . Davies and Pfenning [10] studied the interactions between intersection types and effects in call-by-value languages. And they proposed a “value restriction” for intersection types, similar to value restriction on parametric polymorphism. None of those calculi include a merge operator.

There have been attempts to provide a foundational calculus for Scala that incorporates intersection types [1, 2]. However, the type-soundness of a minimal Scala-like calculus with intersection types and parametric polymorphism is not yet proven. Recently, some form of intersection types has been adopted in object-oriented languages such as Scala, Ceylon, and Grace. Generally speaking, the most significant difference to λ_i is that in all previous systems there is no explicit introduction construct like our merge operator.

Other Type Systems with Intersection Types. Refinement intersection [9, 11, 14] is the more conservative approach of adopting intersection types. It increases only the expressiveness of types but not terms. But without a term-level construct like “merge”, it is not possible to encode various language features. As an alternative to syntactic subtyping described in this paper, Frisch *et al.* [15] studied semantic subtyping. Semantic subtyping seems to have important advantages over syntactic subtyping. One worthy avenue for future work is to study languages with intersection types and merge operator in a semantic subtyping setting.

$\lambda\&$

“the solution seems much more powerful than simply forbidding non-overlapping intersections”

No it is not! $\lambda\&$ rejects intersections that are accepted in our system:

$\text{Int} \rightarrow \text{Char}, \text{Int} \rightarrow \text{Bool}$

This example violates the well-formedness conditions of $\lambda\&$ (see Section 3.2 of “A Calculus for Overloaded Functions with Subtyping” (1995)). So clearly the conditions imposed by $\lambda\&$ (even for the special case of functions) do not subsume disjoint intersections.

“The problem of coherence with intersection types was studied in the 90’s by Castagna in the language $\lambda\&$ ”

No it wasn’t! Castagna studied the overloading problem for functions and focused only on the “merge” (in our sense) of functions. Our work considers a system with **arbitrary** intersection-s/merges and tries to present a coherent subset of that. The well-formedness conditions presented in Section 3.2 of the $\lambda\&$ paper cannot be ported to a system with arbitrary intersections, since they assume function types only.

Moreover, although $\lambda\&$ can encode records, **it** is unclear how to encode arbitrary merges. One failed attempt to encode arbitrary merges in $\lambda\&$ is to consider a record with multiple labels of the same name. For example, encoding l, c as

$l=1, l=c$

(where label l is of an isolated atomic type L , see Section 4 of the $\lambda\&$ paper). However, this is also rejected in $\lambda\&$, since it violates the well-formedness conditions.

Nevertheless $\lambda\&$ is related work and should be discussed.

Traits and Trait Calculi. The seminal paper by Schärli *et al.* introduced the ideas behind traits. In their original paper, they docu-

mented an implementation of the trait mechanism in a dynamically typed version of Smalltalk. Fisher and Reppy [13] presented a statically typed calculus that models traits. λ_i is not dedicated to traits; but rather, it supports a source language that models traits. Compared to Fisher and Reppy’s calculus, λ_i is more lightweight. For example, self references (as well as other OO-specific constructs) are not built-in λ_i . One reason for the difference is that Fisher and Reppy’s calculus supports *classes* in addition to traits, and considers the interaction between them, whereas our object oriented source language is *prototype* (or delegation) based—the mechanism for code reuse is purely traits. Of course, there have been many other formalizations of traits, such as [21]. But most of them are heavyweight and specific to modeling traits and typical class-based models of OOP, and therefore differ from our approach.

Bettini *et al.*’s prototype language, SWRTJ [3] distinguishes, in their terminology, “records” and “traits”—the former contain fields and the latter contain methods. Since we try to model a pure object-oriented language, we have excluded fields, which provide state reuse. In SWRTJ, traits themselves are not meant to be the generator of instances. Instead, another construct, called “classes” are, and make use of traits.

The Scala language also has a notion of “traits”. However, unlike what its name suggests, the semantics of trait composition in Scala is more similar to mixins [4]. That is, like traditional mixin semantics, when two traits are composed, Scala attempts to do *implicit resolution of conflicts*. In comparison, the traits modeled in λ_i are intended to model the original trait idea closely, and conflicts must be resolved explicitly. Schärli *et al.* document well the trade-offs between mixins and traits. Aside from that, Scala’s traits and our source language’s traits have four major differences:

1. Scala’s traits cannot be instantiated but only mixed into a class (which can be anonymous), whereas traits in our language can be instantiated directly.
2. Scala’s traits cannot take constructor parameters whereas ours can. As in the point example below, our trait is itself a constructor and takes the x - and y -coordinates as parameters:

```
trait Point(x: Int, y: Int) { self: Point →
  x() = x
  y() = y
} in ...
```

3. Dynamic instantiation is supported in λ_i , but not in Scala. In Scala instantiating an object from a class or traits requires that all classes or traits are statically known.
4. Our model of traits is purely functional, but Scala’s traits also support fields, mutable state and abstract types.

7. Conclusion and Future Work

This paper described λ_i : a language that combines intersection types and a merge operator. The language is proved to be type-safe and coherent. To ensure coherence the type system accepts only disjoint intersections. We believe that disjoint intersection types are intuitive, and at the same time expressive. We have shown the applicability of disjoint intersection types to model a simple form of traits.

We implemented the core functionalities of the λ_i as part of a JVM-based compiler. Based on the type system of λ_i , we have built an ML-like source language compiler that offers interoperability with Java (such as object creation and method calls). The source language is loosely based on the more general System F_ω and supports a number of other features, including records, polymorphism, mutually recursive `let` bindings, type aliases, algebraic data types,

pattern matching, and first-class modules that are encoded using `let rec` and records.

For the future, we intend to improve our source language and show the power of disjoint intersection types in large case studies. One pressing challenge is to address the intersection between disjoint intersection types and polymorphism. We are also interested in extending our work to systems with a \top type. This will also require an adjustment to the notion of disjoint types. A suitable notion of disjointness between two types A and B in the presence of \top would be to require that the only common supertype of A and B is \top . Finally we would like to study the addition of union types. This will also require changes in our notion of disjointness, since with union types there always exists a type $A|B$, which is the common supertype of two types A and B .

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