

Higher-rank Polymorphism: Type Inference and Extensions

by

Ningning Xie
(谢宁宁)



A thesis submitted in partial fulfillment of the requirements for
the degree of Doctor of Philosophy
at The University of Hong Kong

February 2021

Abstract of thesis entitled
“Higher-rank Polymorphism: Type Inference and Extensions”

Submitted by
Ningning Xie

for the degree of Doctor of Philosophy
at The University of Hong Kong
in February 2021

DECLARATION

I declare that this thesis represents my own work, except where due acknowledgment is made, and that it has not been previously included in a thesis, dissertation or report submitted to this University or to any other institution for a degree, diploma or other qualifications.

.....

Ningning Xie

February 2021

ACKNOWLEDGMENTS

CONTENTS

DECLARATION	I
ACKNOWLEDGMENTS	III
LIST OF FIGURES	VII
LIST OF TABLES	IX
I PROLOGUE	1
1 INTRODUCTION	3
1.1 Contributions	3
1.2 Organization	5
2 BACKGROUND	7
2.1 The Hindley-Milner Type System	7
2.1.1 Syntax	7
2.1.2 Static Semantics	8
2.1.3 Principal Type Scheme	9
2.1.4 Algorithmic Type System	9
2.2 The Odersky-Läufer Type System	10
2.2.1 Higher-rank Types	10
2.2.2 Syntax	10
2.2.3 Static Semantics	11
2.2.4 Relating to HM	13
2.3 The Dunfield-Krishnaswami Type System	14
2.3.1 Bidirectional Type Checking	14
2.3.2 Syntax	14
2.3.3 Static Semantics	15
2.3.4 Algorithmic Type System	18

II	TYPE INFERENCE	19
3	BIDIRECTIONAL TYPE CHECKING WITH THE APPLICATION MODE	21
3.1	Introduction	21
3.1.1	Revisiting Bidirectional Type Checking	21
3.1.2	Type Checking with The Application Mode	22
3.1.3	Benefits of Information Flowing from Arguments to Functions	25
4	UNIFICATION WITH PROMOTION	27
III	EXTENSIONS	29
5	HIGHER RANK GRADUAL TYPES	31
6	DEPENDENT TYPES	33
IV	RELATED AND FUTURE WORK	35
7	RELATED WORK	37
8	FUTURE WORK	39
V	EPILOGUE	41
9	CONCLUSION	43
	BIBLIOGRAPHY	45
VI	TECHNICAL APPENDIX	49

LIST OF FIGURES

2.1	Syntax and static semantics of the Hindley-Milner type system.	8
2.2	Subtyping in the Hindley-Milner type system.	9
2.3	Syntax of the Odersky-Läufer type system.	11
2.4	Well-formedness of types in the Odersky-Läufer type system.	11
2.5	Static semantics of the Odersky-Läufer type system.	12
2.6	Syntax of the Dunfield-Krishnaswami Type System	15
2.7	Static semantics of the Dunfield-Krishnaswami type system.	16

LIST OF TABLES

PART I

PROLOGUE

1 INTRODUCTION

mention that in this thesis when we say “higher-rank polymorphism” we mean “predicative implicit higher-rank polymorphism”.

1.1 CONTRIBUTIONS

In summary the contributions of this thesis are:

- Part II**
- Chapter 3 proposes a new design for type inference of higher-rank polymorphism.
 - We design a variant of bi-directional type checking where the inference mode is combined with a new, so-called, application mode. The application mode naturally propagates type information from arguments to the functions.
 - With the application mode, we give a new design for type inference of higher-rank polymorphism, which generalizes the HM type system, supports a polymorphic let as syntactic sugar, and infers higher rank types. We present a syntax-directed specification, an elaboration semantics to System F, and an algorithmic type system with completeness and soundness proofs.
 - Chapter 4 presents a new approach for implementing unification.
 - We propose a process named *promotion*, which, given a unification variable and a type, promotes the type so that all unification variables in the type are well-typed with regard to the unification variable.
 - We apply promotion in a new implementation of the unification procedure in higher-rank polymorphism, and show that the new implementation is sound and complete.
- Part III**
- Chapter 5 extends higher-rank polymorphism with gradual types.
 - We define a framework for consistent subtyping with

- - ★ a new definition of consistent subtyping that subsumes and generalizes that of Siek and Taha [2007] and can deal with polymorphism and top types;
 - ★ and a syntax-directed version of consistent subtyping that is sound and complete with respect to our definition of consistent subtyping, but still guesses instantiations.
- Based on consistent subtyping, we present the calculus GPC. We prove that our calculus satisfies the static aspects of the refined criteria for gradual typing [Siek et al. 2015], and is type-safe by a type-directed translation to λB [Ahmed et al. 2009].
- We present a sound and complete bidirectional algorithm for implementing the declarative system based on the design principle of Garcia and Cimini [2015].
- Chapter 6 further explores the design of promotion in the context of kind inference for datatypes.
 - We formalize Haskell98’s datatype declarations, providing both a declarative specification and syntax-driven algorithm for kind inference. We prove that the algorithm is sound and observe how Haskell98’s technique of defaulting unconstrained kinds to \star leads to incompleteness. We believe that ours is the first formalization of this aspect of Haskell98.
 - We then present a type and kind language that is unified and dependently typed, modeling the challenging features for kind inference in modern Haskell. We include both a declarative specification and a syntax-driven algorithm. The algorithm is proved sound, and we observe where and why completeness fails. In the design of our algorithm, we must choose between completeness and termination; we favor termination but conjecture that an alternative design would regain completeness. Unlike other dependently typed languages, we retain the ability to infer top-level kinds instead of relying on compulsory annotations.

Many metatheory in the paper comes with Coq proofs, including type safety, coherence, etc.¹

¹For convenience, whenever possible, definitions, lemmas and theorems have hyperlinks (click ) to their Coq counterparts.

1.2 ORGANIZATION

This thesis is largely based on the publications by the author [Xie et al. 2018, 2019a,b; Xie and Oliveira 2017, 2018], as indicated below.

Chapter 3: Ningning Xie and Bruno C. d. S. Oliveira. 2018. “Let Arguments Go First”. In *European Symposium on Programming (ESOP)*.

Chapter 4: Ningning Xie and Bruno C. d. S. Oliveira. 2017. “Towards Unification for Dependent Types” (Extended abstract), In *Draft Proceedings of Trends in Functional Programming (TFP)*.

Chapter 5: Ningning Xie, Xuan Bi, and Bruno C. d. S. Oliveira. 2018. “Consistent Subtyping for All”. In *European Symposium on Programming (ESOP)*.

Ningning Xie, Xuan Bi, Bruno C. d. S. Oliveira, and Tom Schrijvers. 2019. “Consistent Subtyping for All”. In *ACM Transactions on Programming Languages and Systems (TOPLAS)*.

Chapter 6: Ningning Xie, Richard Eisenberg and Bruno C. d. S. Oliveira. 2020. “Kind Inference for Datatypes”. In *Symposium on Principles of Programming Languages (POPL)*.

2 BACKGROUND

This chapter sets the stage for type systems in later chapters. Section 2.1 reviews the Hindley-Milner type system [Damas and Milner 1982; Hindley 1969; Milner 1978], a classical type system for the lambda calculus with parametric polymorphism. We first review its syntax and semantics, then discuss the property of principality, and finally talk briefly about its algorithmic system. Section 2.2 presents the Odersky-Läufer type system [Odersky and Läufer 1996], which extends upon the Hindley-Milner type system by putting higher-rank type annotations to work. Finally in Section 2.3 we introduce the Dunfield-Krishnaswami type system, a bidirectional higher-rank type system.

2.1 THE HINDLEY-MILNER TYPE SYSTEM

The global type-inference algorithms employed in modern functional languages such as ML, Haskell and OCaml, are derived from the Hindley-Milner type system. The Hindley-Milner type system, hereafter referred to as HM, is a polymorphic type discipline first discovered in Hindley [1969], later rediscovered by Milner [1978], and also closely formalized by Damas and Milner [1982].

2.1.1 SYNTAX

The syntax of HM is given in Figure 2.1. The expressions e include variables x , literals n , lambda abstractions $\lambda x. e$, applications $e_1 e_2$ and **let** $x = e_1$ **in** e_2 . Note here lambda abstractions have no type annotations, and the type information is to be reconstructed by the type system.

Types consist of polymorphic types σ and monomorphic types (monotypes) τ . A polymorphic type is a sequence of universal quantifications (which can be empty) followed by a monotype τ , which can be the integer type Int , type variables a and function types $\tau_1 \rightarrow \tau_2$.

A context Ψ tracks the type information for variables. We implicitly assume items in a context are distinct throughout the thesis.

2 Background

Expressions	$e ::= x \mid n \mid \lambda x. e \mid e_1 e_2 \mid \mathbf{let} \ x = e_1 \ \mathbf{in} \ e_2$
Types	$\sigma ::= \forall \bar{a}^i. \tau$
Monotypes	$\tau ::= \mathbf{Int} \mid a \mid \tau_1 \rightarrow \tau_2$
Contexts	$\Psi ::= \bullet \mid \Psi, x : \sigma$

$\Psi \vdash^{HM} e : \sigma$

(Typing)

$\frac{\text{HM-VAR} \quad (x : \sigma) \in \Psi}{\Psi \vdash^{HM} x : \sigma}$	$\frac{\text{HM-INT}}{\Psi \vdash^{HM} n : \mathbf{Int}}$	$\frac{\text{HM-LAM} \quad \Psi, x : \tau_1 \vdash^{HM} e : \tau_2}{\Psi \vdash^{HM} \lambda x. e : \tau_1 \rightarrow \tau_2}$
$\frac{\text{HM-APP} \quad \Psi \vdash^{HM} e_1 : \tau_1 \rightarrow \tau_2 \quad \Psi \vdash^{HM} e_2 : \tau_1}{\Psi \vdash^{HM} e_1 e_2 : \tau_2}$	$\frac{\text{HM-LET} \quad \Psi \vdash^{HM} e_1 : \sigma \quad \Psi, x : \sigma \vdash^{HM} e_2 : \tau}{\Psi \vdash^{HM} \mathbf{let} \ x = e_1 \ \mathbf{in} \ e_2 : \tau}$	
$\frac{\text{HM-GEN} \quad \bar{a}^i \notin \text{FV}(\Psi) \quad \Psi \vdash^{HM} e : \tau}{\Psi \vdash^{HM} e : \forall \bar{a}^i. \tau}$	$\frac{\text{HM-INST} \quad \Psi \vdash^{HM} e : \forall \bar{a}^i. \tau}{\Psi \vdash^{HM} e : \tau[\bar{a}_i \mapsto \bar{\tau}_i^i]}$	

Figure 2.1: Syntax and static semantics of the Hindley-Milner type system.

2.1.2 STATIC SEMANTICS

The declarative typing judgment $\Psi \vdash^{HM} e : \sigma$ derives the type σ of the expression e under the context Ψ . Rule [HM-VAR](#) fetches a polymorphic type $x : \sigma$ from the context. Literals always have the integer type (rule [HM-INT](#)). For lambdas (rule [HM-LAM](#)), since there is no type for the binder given, the system *guesses* a *monotype* τ_1 as the type of x , and derives the type τ_2 for the body e , returning a function $\tau_1 \rightarrow \tau_2$. Function types are eliminated by applications. In rule [HM-APP](#), the type of the argument must match the parameter's type τ_1 , and the whole application returns type τ_2 .

Rule [HM-LET](#) is the key rule for flexibility in HM, where a *polymorphic* expression can be defined, and later instantiated with different types in the call sites. In this rule, the expression e_1 has a polymorphic type σ , and the rule adds $x : \sigma$ into the context to type-check e_2 .

Rule [HM-GEN](#) and rule [HM-INST](#) correspond to *generalization* and *instantiation* respectively. In rule [HM-GEN](#), we can generalize over type variables \bar{a}^i which are not bound in the type context Ψ . In rule [HM-INST](#), we can instantiate the type variables with arbitrary *monotypes*.

$$\boxed{\vdash^{HM} \sigma_1 <: \sigma_2} \quad (Subtyping)$$

$$\begin{array}{c}
\text{HM-S-REFL} \\
\hline
\vdash^{HM} \tau <: \tau
\end{array}
\quad
\begin{array}{c}
\text{HM-S-FORALLR} \\
\frac{a \notin \text{FV}(\sigma_1) \quad \vdash^{HM} \sigma_1 <: \sigma_2}{\vdash^{HM} \sigma_1 <: \forall a. \sigma_2}
\end{array}
\quad
\begin{array}{c}
\text{HM-S-FORALLL} \\
\frac{\vdash^{HM} \sigma_1[a \mapsto \tau] <: \sigma_2}{\vdash^{HM} \forall a. \sigma_1 <: \sigma_2}
\end{array}$$

Figure 2.2: Subtyping in the Hindley-Milner type system.

2.1.3 PRINCIPAL TYPE SCHEME

One salient feature of HM is that the system enjoys the existence of *principal types*, without requiring any type annotations. Before we present the definition of principal types, let's first define the *subtyping* relation among types.

The judgment $\vdash^{HM} \sigma_1 <: \sigma_2$, given in Figure 2.2, reads that σ_1 is a subtype of σ_2 . The subtyping relation indicates that σ_1 is more *general* than σ_2 : for any instantiation of σ_2 , we can find an instantiation of σ_1 to make two types match. Rule **HM-S-REFL** is simply reflexive for monotypes. Rule **HM-S-FORALLR** has a polymorphic type $\forall a. \sigma_2$ on the right hand side. In order to prove the subtyping relation for *all* possible instantiation of a , we *skolemize* a , by making sure a does not appear in σ_1 (up to α -renaming). In this case, if σ_1 is still a subtype of σ_2 , we are sure then whatever a can be instantiated to, σ_1 can be instantiated to match σ_2 . In rule **HM-S-FORALLL**, by contrast, the a in $\forall a. \sigma_1$ can be instantiated to any monotype to match the right hand side. For example:

$$\begin{array}{lcl}
\text{Int} \rightarrow \text{Int} & <: & \text{Int} \rightarrow \text{Int} \\
\forall a. a \rightarrow a & <: & \text{Int} \rightarrow \text{Int}
\end{array}$$

Given the subtyping relation, now we can formally state that HM enjoys *principality*. That is, for every well-typed expression in HM, there exists one type for the expression, which is more general than any other types the expression can derive. Formally,

Theorem 2.1 (Principality for HM). *If $\Psi \vdash^{HM} e : \sigma$, then there exists σ' such that $\Psi \vdash^{HM} e : \sigma'$, and for all σ such that $\Psi \vdash^{HM} e : \sigma$, we have $\vdash^{HM} \sigma' <: \sigma$.*

Consider the expression $\lambda x. x$. It has a principal type $\forall a. a \rightarrow a$, which is more general than other options, e.g., $\text{Int} \rightarrow \text{Int}$, $(\text{Int} \rightarrow \text{Int}) \rightarrow (\text{Int} \rightarrow \text{Int})$, etc.

2.1.4 ALGORITHMIC TYPE SYSTEM

The declarative specification of HM given in Figure 2.1 does not directly lead to an algorithm, because there are still many guesses in the system, such as in rule **HM-LAM**.

There exists a sound and complete type inference algorithm for HM [Damas and Milner 1982], which has served as the basis for the type inference algorithm for many other systems [Jones et al. 2007; Odersky and Läufer 1996], including the system presented in Chapter 3. We will discuss more about it in Chapter 3.

2.2 THE ODERSKY-LÄUFER TYPE SYSTEM

The HM system is simple, flexible and powerful. However, since the type annotations in lambda abstractions are always missing, HM only derives polymorphic types of *rank 1*. That is, universal quantifiers only appear at the top level. Polymorphic types are of *higher-rank*, if universal quantifiers can appear anywhere in a type. Odersky and Läufer [1996] proposed a type system, hereafter referred to as OL, which extends HM by allowing lambda abstractions to have explicit *higher-rank* types as type annotations.

2.2.1 HIGHER-RANK TYPES

We define the rank of types as follows.

Definition 1 (Type rank). The *rank* of a type is the depth at which universal quantifiers appear contravariantly [Kfoury and Tiuryn 1992]. Formally,

$$\begin{array}{rcl}
 \text{rank}(\tau) & = & 0 \\
 \text{rank}(\sigma_1 \rightarrow \sigma_2) & = & \max(\text{rank}(\sigma_1) + 1, \text{rank}(\sigma_2)) \\
 \text{rank}(\forall a. \sigma) & = & \max(1, \text{rank}(\sigma))
 \end{array}$$

Below we give some examples:

$$\begin{array}{rcl}
 \text{rank}(\text{Int} \rightarrow \text{Int}) & = & 0 \\
 \text{rank}(\forall a. a \rightarrow a) & = & 1 \\
 \text{rank}(\text{Int} \rightarrow (\forall a. a \rightarrow a)) & = & 1 \\
 \text{rank}((\forall a. a \rightarrow a) \rightarrow \text{Int}) & = & 2
 \end{array}$$

From the definition, we can see that monotypes always have rank 0, and the polymorphic types in HM (σ in Figure 2.1) has at most rank 1.

2.2.2 SYNTAX

The syntax of OL is given in Figure 2.3. Comparing to HM, we observe the following differences.

Expressions	e	$::=$	$x \mid n \mid \lambda x : \sigma. e \mid \lambda x. e \mid e_1 e_2 \mid \mathbf{let} \ x = e_1 \mathbf{in} \ e_2$
Types	σ	$::=$	$\mathbf{Int} \mid a \mid \sigma_1 \rightarrow \sigma_2 \mid \forall a. \sigma$
Monotypes	τ	$::=$	$\mathbf{Int} \mid a \mid \tau_1 \rightarrow \tau_2$
Contexts	Ψ	$::=$	$\bullet \mid \Psi, x : \sigma \mid \Psi, a$

Figure 2.3: Syntax of the Odersky-Läufer type system.

$\Psi \vdash^{OL} \sigma$	(Type Well-formedness)		
OL-WF-INT	OL-WF-TVAR	OL-WF-ARROW	OL-WF-FORALL
$\frac{}{\Psi \vdash^{OL} \mathbf{Int}}$	$\frac{a \in \Psi}{\Psi \vdash^{OL} a}$	$\frac{\Psi \vdash^{OL} \sigma_1 \quad \Psi \vdash^{OL} \sigma_2}{\Psi \vdash^{OL} \sigma_1 \rightarrow \sigma_2}$	$\frac{\Psi, a \vdash^{OL} \sigma}{\Psi \vdash^{OL} \forall a. \sigma}$

Figure 2.4: Well-formedness of types in the Odersky-Läufer type system.

First, expressions e include not only unannotated lambda abstractions $\lambda x. e$, but also annotated lambda abstractions $\lambda x : \sigma. e$, where the type annotation σ is a polymorphic type. Thus unlike HM, the argument type for a function is not limited to a monotype.

Second, the polymorphic types σ now include the integer type \mathbf{Int} , type variables a , functions $\sigma_1 \rightarrow \sigma_2$ and universal quantifications $\forall a. \sigma$. Since the argument type in a function can be polymorphic, we see that OL supports *arbitrary* rank of types. The definition of monotypes remains the same. Obviously polymorphic types still subsume monotypes.

Finally, in addition to variable types, the contexts Ψ now also keep track of type variables. Note that in the original work in Odersky and Läufer [1996], the system, much like HM, does not track type variables; instead, it explicitly checks that type variables are fresh with respect to a context or a type when needed. Here we include type variables in contexts, as it sets us well for the Dunfield-Krishnaswami type system to be introduced in the next section. Moreover, the differences do not change the essence of the type system, and it provides a complete view of the possible formalism of contexts in a type system with generalization. As before, we assume all items in a context are distinct.

Now for a type to be well-formedness, it must have all its free variable bound in the context. The type well-formedness rules are given in Figure 2.4. All rules are straightforward.

2.2.3 STATIC SEMANTICS

The static semantics of OL is given in Figure 2.5.

Rule **OL-VAR** and rule **OL-INT** are the same as that of HM. Rule **OL-LAMANN** type-checks annotated lambda abstractions, by simply putting $x : \sigma$ into the context to type the body. For

2 Background

$\Psi \vdash^{OL} e : \sigma$

(Typing)

$\frac{\text{OL-VAR} \quad (x : \sigma) \in \Psi}{\Psi \vdash^{OL} x : \sigma}$	$\frac{\text{OL-INT}}{\Psi \vdash^{OL} n : \text{Int}}$	$\frac{\text{OL-LAMANN} \quad \Psi, x : \sigma_1 \vdash^{OL} e : \sigma_2}{\Psi \vdash^{OL} \lambda x : \sigma_1. e : \sigma_1 \rightarrow \sigma_2}$
$\frac{\text{OL-LAM} \quad \Psi \vdash^{OL} \tau \quad \Psi, x : \tau \vdash^{OL} e : \sigma}{\Psi \vdash^{OL} \lambda x. e : \tau \rightarrow \sigma}$	$\frac{\text{OL-APP} \quad \Psi \vdash^{OL} e_1 : \sigma_1 \rightarrow \sigma_2 \quad \Psi \vdash^{OL} e_2 : \sigma_1}{\Psi \vdash^{OL} e_1 e_2 : \sigma_2}$	
$\frac{\text{OL-LET} \quad \Psi \vdash^{OL} e_1 : \sigma_1 \quad \Psi, x : \sigma_1 \vdash^{OL} e_2 : \sigma_2}{\Psi \vdash^{OL} \text{let } x = e_1 \text{ in } e_2 : \sigma_2}$	$\frac{\text{OL-GEN} \quad \Psi, a \vdash^{OL} e : \sigma}{\Psi \vdash^{OL} e : \forall a. \sigma}$	
$\frac{\text{OL-SUB} \quad \Psi \vdash^{OL} e : \sigma_1 \quad \Psi \vdash \sigma_1 <: \sigma_2}{\Psi \vdash^{OL} e : \sigma_2}$		

$\Psi \vdash^{OL} \sigma_1 <: \sigma_2$

(Subtyping)

$\frac{\text{OL-S-TVAR} \quad a \in \Psi}{\Psi \vdash^{OL} a <: a}$	$\frac{\text{OL-S-INT}}{\Psi \vdash^{OL} \text{Int} <: \text{Int}}$	$\frac{\text{OL-S-ARROW} \quad \Psi \vdash^{OL} \sigma_3 <: \sigma_1 \quad \Psi \vdash^{OL} \sigma_2 <: \sigma_4}{\Psi \vdash^{OL} \sigma_1 \rightarrow \sigma_2 <: \sigma_3 \rightarrow \sigma_4}$
$\frac{\text{OL-S-FORALLL} \quad \Psi \vdash^{OL} \tau \quad \Psi \vdash^{OL} \sigma[a \mapsto \tau] <: \sigma_2}{\Psi \vdash^{OL} \forall a. \sigma_1 <: \sigma_2}$	$\frac{\text{OL-S-FORALLR} \quad \Psi, a \vdash^{OL} \sigma_1 <: \sigma_2}{\Psi \vdash^{OL} \sigma_1 <: \forall a. \sigma_2}$	

Figure 2.5: Static semantics of the Odersky-Läufer type system.

unannotated lambda abstractions in rule **OL-LAM**, the system still guesses a mere monotype. That is, the system never guesses a polymorphic type for lambdas; instead, an explicit polymorphic type annotation is required. Rule **OL-APP**, rule **OL-LET** are similar as HM, except that polymorphic types may appear in return types. In the generalization rule **OL-GEN**, we put a new type variable a into the context, and the return type σ is then generalized over a , returning $\forall a. \sigma$.

The subsumption rule **OL-SUB** is crucial for OL, which allows an expression of type σ_1 to have type σ_2 with σ_1 being a subtype of σ_2 ($\Psi \vdash \sigma_1 <: \sigma_2$). Note that the instantiation rule **HM-INST** in HM is a special case of rule **OL-SUB**, as we have $\forall \bar{a}^i. \tau <: \tau[\bar{a}_i \mapsto \bar{\tau}_i^i]$ by applying rule **HM-S-FORALL** repeatedly.

The subtyping relation of OL $\Psi \vdash^{OL} \sigma_1 <: \sigma_2$ also generalizes the subtyping relation of HM. In particular, in rule **OL-S-ARROW**, functions are *contravariant* on arguments, and *covariant* on return types. This rule allows us to compare higher-rank polymorphic types, rather than just polymorphic types with universal quantifiers only at the top level. For example,

$$\begin{array}{ll} \Psi \vdash^{OL} \forall a. a \rightarrow a & <: \text{Int} \rightarrow \text{Int} \\ \Psi \vdash^{OL} \text{Int} \rightarrow (\forall a. a \rightarrow a) & <: \text{Int} \rightarrow (\text{Int} \rightarrow \text{Int}) \\ \Psi \vdash^{OL} (\text{Int} \rightarrow \text{Int}) \rightarrow \text{Int} & <: (\forall a. a \rightarrow a) \rightarrow \text{Int} \end{array}$$

PREDICATIVITY. In a system with high-ranker types, one important design decision to make is whether the system is *predicative* or *impredicative*. A system is predicative, if the type variable bound by a universal quantifier is only allowed to be substituted by a monotype; otherwise it is impredicative. It is well-known that general type inference for impredicativity is undecidable [Wells 1999]. OL is predicative, which can be seen from rule **OL-S-FORALL**. We focus only on predicative type systems throughout the thesis.

2.2.4 RELATING TO HM

It can be proved that OL is a conservative extension of HM. That is, every well-typed expression in HM is well-typed in OL, modulo the different representation of contexts.

Theorem 2.2 (Odersky-Läufer type system conservative over Hindley-Milner type system). *If $\Psi \vdash^{HM} e : \sigma$, suppose Ψ' is Ψ extended with type variables in Ψ and σ , then $\Psi' \vdash^{OL} e : \sigma$.*

Moreover, since OL is predicative and only guesses monotypes for unannotated lambda abstractions, its algorithmic system can be implemented as a direct extension of the one for HM.

2.3 THE DUNFIELD-KRISHNASWAMI TYPE SYSTEM

Both HM and OL derive only monotypes for unannotated lambda abstractions. OL improves on HM by allowing polymorphic lambda abstractions but requires the polymorphic type annotations are given explicitly. The Dunfield-Krishnaswami type system [Dunfield and Krishnaswami 2013], hereafter referred to as DM, give a *bidirectional* account of higher-rank polymorphism, where type information can be propagated through the syntax tree. Therefore, it is possible for a variable bound in a lambda abstraction without explicit type annotations to get a polymorphic type.

2.3.1 BIDIRECTIONAL TYPE CHECKING

Bidirectional type checking has been known in the folklore of type systems for a long time. It was popularized by Pierce and Turner’s work on local type inference [Pierce and Turner 2000]. Local type inference was introduced as an alternative to HM type systems, which could easily deal with polymorphic languages with subtyping. The key idea in local type inference is simple.

“... are local in the sense that missing annotations are recovered using only information from adjacent nodes in the syntax tree, without long-distance constraints such as unification variables.”

Bidirectional type checking is one component of local type inference that, aided by some type annotations, enables type inference in an expressive language with polymorphism and subtyping. In its basic form typing is split into *inference* and *checking* modes. The most salient feature of a bidirectional type-checker is when information deduced from inference mode is used to guide checking of an expression in checked mode.

Since Pierce and Turner’s work, various other authors have proved the effectiveness of bidirectional type checking in several other settings, including many different systems with subtyping [Davies and Pfenning 2000; Dunfield and Pfenning 2004], systems with dependent types [Asperti et al. 2012; Coquand 1996; Löh et al. 2010; Xi and Pfenning 1999], etc. In particular, bidirectional type checking has also been combined with HM-style techniques for providing type inference in the presence of higher-rank type, including DK and Jones et al. [2007].

2.3.2 SYNTAX

The syntax of the DK is given in Figure 2.6. Comparing to OL, only the definition of expressions slightly differs. First, the expressions e in DK have no let expressions. Dunfield

Expressions	e	$::=$	$x \mid n \mid \lambda x : \sigma. e \mid \lambda x. e \mid e_1 e_2 \mid e : \sigma$
Types	σ	$::=$	$\text{Int} \mid a \mid \sigma_1 \rightarrow \sigma_2 \mid \forall a. \sigma$
Monotypes	τ	$::=$	$\text{Int} \mid a \mid \tau_1 \rightarrow \tau_2$
Contexts	Ψ	$::=$	$\bullet \mid \Psi, x : \sigma \mid \Psi, a$

Figure 2.6: Syntax of the Dunfield-Krishnaswami Type System

and Krishnaswami [2013] omitted let-binding from the formal development, but argued that restoring let-bindings is easy, as long as they get no special treatment incompatible with substitution (e.g., a syntax-directed HM does polymorphic generalization only at let-bindings). Second, DK has annotated expressions $e : \sigma$, in which the type annotation can be propagated inward the expression, as we will see shortly.

The definitions of types and contexts are the same as in OL. Thus, DK also shares the same well-formedness definition as in OL (Figure 2.4). We thus omit the definitions, but use \vdash^{DK} to denote the corresponding judgment in DK.

2.3.3 STATIC SEMANTICS

Figure 2.7 presents the typing rules for DK. The system uses bidirectional type checking to accommodate polymorphism. Traditionally, two modes are employed in bidirectional systems: the inference mode $\Psi \vdash^{DK} e \Rightarrow \sigma$, which takes a term e and produces a type σ , similar to the judgment $\Psi \vdash^{HM} e : \sigma$ or $\Psi \vdash^{OL} e : \sigma$ in previous systems; the checking mode $\Psi \vdash^{DK} e \Leftarrow \sigma$, which takes a term e and a type σ as input, and ensures that the term e checks against σ . We first discuss rules in the inference mode.

TYPE INFERENCE. Rule **DK-INF-VAR** and rule **DK-INF-INT** are straightforward. To infer unannotated lambdas, rule **DK-INF-LAM** guesses a monotype. For an application $e_1 e_2$, rule **DK-INF-APP** first infers the type σ of the expression e_1 . Then, because e_1 is applied to an argument, the type σ is decomposed into a function type $\sigma_1 \rightarrow \sigma_2$, using the matching judgment (discussed shortly). Now since the function expects an argument of type σ_1 , the rule proceeds by checking e_2 against σ_1 . Similarly, for an annotated expression $e : \sigma$, rule **DK-INF-ANNO** simply checks e against σ . Both rules (rule **DK-INF-APP** and rule **DK-INF-ANNO**) have mode switched from inference to checking.

TYPE CHECKING. Now we turn to the checking mode. When an expression is checked against a type, the expression is expected to have that type. More importantly, the checking mode allows us to push the type information into the expressions.

2 Background

$\Psi \vdash^{DK} e \Rightarrow \sigma$

(Type Inference)

$$\begin{array}{c}
\text{DK-INF-VAR} \\
\frac{(x : \sigma) \in \Psi}{\Psi \vdash^{DK} x \Rightarrow \sigma}
\end{array}
\quad
\begin{array}{c}
\text{DK-INF-INT} \\
\frac{}{\Psi \vdash^{DK} n \Rightarrow \text{Int}}
\end{array}
\quad
\begin{array}{c}
\text{DK-INF-LAM} \\
\frac{\Psi \vdash^{DK} \tau_1 \rightarrow \tau_2 \quad \Psi, x : \tau_1 \vdash^{DK} e \Rightarrow \tau_2}{\Psi \vdash^{DK} \lambda x. e \Rightarrow \tau_1 \rightarrow \tau_2}
\end{array}$$

$$\begin{array}{c}
\text{DK-INF-APP} \\
\frac{\Psi \vdash^{DK} \sigma \triangleright \sigma_1 \rightarrow \sigma_2 \quad \Psi \vdash^{DK} e_1 \Rightarrow \sigma \quad \Psi \vdash^{DK} e_2 \Leftarrow \sigma_1}{\Psi \vdash^{DK} e_1 e_2 \Rightarrow \sigma_2}
\end{array}
\quad
\begin{array}{c}
\text{DK-INF-ANNO} \\
\frac{\Psi \vdash^{DK} e \Leftarrow \sigma}{\Psi \vdash^{DK} e : \sigma \Rightarrow \sigma}
\end{array}$$

$\Psi \vdash^{DK} e \Leftarrow \sigma$

(Type Checking)

$$\begin{array}{c}
\text{DK-CHK-INT} \\
\frac{}{\Psi \vdash^{DK} n \Leftarrow \text{Int}}
\end{array}
\quad
\begin{array}{c}
\text{DK-CHK-LAM} \\
\frac{\Psi, x : \sigma_1 \vdash^{DK} e \Leftarrow \sigma_2}{\Psi \vdash^{DK} \lambda x. e \Leftarrow \sigma_1 \rightarrow \sigma_2}
\end{array}
\quad
\begin{array}{c}
\text{DK-CHK-GEN} \\
\frac{\Psi, a \vdash^{DK} e \Leftarrow \sigma}{\Psi \vdash^{DK} e \Leftarrow \forall a. \sigma}
\end{array}$$

$$\begin{array}{c}
\text{DK-CHK-SUB} \\
\frac{\Psi \vdash^{DK} e \Rightarrow \sigma_1 \quad \Psi \vdash^{DK} \sigma_1 <: \sigma_2}{\Psi \vdash^{DK} e \Leftarrow \sigma_2}
\end{array}$$

$\Psi \vdash^{DK} \sigma_1 \triangleright \sigma_2$

(Matching)

$$\begin{array}{c}
\text{DK-M-FORALL} \\
\frac{\Psi \vdash^{DK} \tau \quad \Psi \vdash^{DK} \sigma[a \mapsto \tau] \triangleright \sigma_1 \rightarrow \sigma_2}{\Psi \vdash^{DK} \forall a. \sigma \triangleright \sigma_1 \rightarrow \sigma_2}
\end{array}
\quad
\begin{array}{c}
\text{DK-M-ARR} \\
\frac{}{\Psi \vdash^{DK} \sigma_1 \rightarrow \sigma_2 \triangleright \sigma_1 \rightarrow \sigma_2}
\end{array}$$

Figure 2.7: Static semantics of the Dunfield-Krishnaswami type system.

Rule **DK-CHK-INT** checks literals against the integer type `Int`. Rule **DK-CHK-LAM** is where the system benefits from bidirectional type checking: the type information gets pushed inside an lambda. For an unannotated lambda abstraction $\lambda x. e$, recall that in the inference mode, we can only guess a monotype for x . With the checking mode, when $\lambda x. e$ is checked against $\sigma_1 \rightarrow \sigma_2$, we do not need to guess any type. Instead, x gets directly the (possibly polymorphic) argument type σ_1 . Then the rule proceeds by checking e with σ_2 , allowing the type information to be pushed further inside. Note how rule **DK-CHK-LAM** improves over HM and OL, by allowing lambda abstractions to have a polymorphic argument type without requiring type annotations.

Rule **DK-CHK-GEN** deals with a polymorphic type $\forall a. \sigma$, by putting the (fresh) type variable a into the context to check e against σ . Rule **DK-CHK-SUB** switches the mode from checking to inference: an expression e can be checked against σ_2 , if e infers the type σ_1 and σ_1 is a subtype of σ_2 .

MATCHING. In rule **DK-INF-APP** where we type-check an application $e_1 e_2$, we derive that e_1 has type σ , but e_1 must have a function type so that it can be applied to an argument. The *matching* judgment instantiates σ into a function.

Matching has two straightforward rules: rule **DK-M-FORALL** instantiates a polymorphic type, by substituting a with a well-formed monotype τ , and continues matching on $\sigma[a \mapsto \tau]$; rule **DK-M-ARR** returns the function type directly.

In Dunfield and Krishnaswami [2013], they use an *application judgment* instead of matching. The application judgment $\Psi \vdash^{DK} \sigma_1 \cdot e \Rightarrow \sigma_2$, whose definition is given below, is interpreted as, when we apply an expression of type σ_1 to the expression e , we get a return type σ_2 .

$$\boxed{\Psi \vdash^{DK} \sigma_1 \cdot e \Rightarrow \sigma_2} \quad (\text{Application})$$

$$\begin{array}{c}
 \text{DK-APP-FORALL} \\
 \frac{\Psi \vdash^{DK} \tau \quad \Psi \vdash^{DK} \sigma[a \mapsto \tau] \cdot e \Rightarrow \sigma_1 \rightarrow \sigma_2}{\Psi \vdash^{DK} \forall a. \sigma \cdot e \Rightarrow \sigma_1 \rightarrow \sigma_2}
 \end{array}
 \qquad
 \begin{array}{c}
 \text{DK-APP-ARR} \\
 \frac{\Psi \vdash^{DK} e \Leftarrow \sigma_1}{\Psi \vdash^{DK} \sigma_1 \rightarrow \sigma_2 \cdot e \Rightarrow \sigma_2}
 \end{array}$$

With the application judgment, rule **DK-INF-APP** is replaced by rule **DK-INF-APP2**.

$$\begin{array}{c}
 \text{DK-INF-APP2} \\
 \frac{\Psi \vdash^{DK} e_1 \Rightarrow \sigma \quad \Psi \vdash^{DK} \sigma \cdot e_2 \Rightarrow \sigma_2}{\Psi \vdash^{DK} e_1 e_2 \Rightarrow \sigma_2}
 \end{array}$$

It can be easily shown that the presentation of rule **DK-INF-APP** with matching is equivalent to that of rule **DK-INF-APP2** with the application judgment. Essentially, they both make sure

2 Background

that the expression being applied has an arrow type $\sigma_1 \rightarrow \sigma_2$, and then check the argument against σ_1 .

We prefer the presentation of rule [DK-INF-APP](#) with matching, as matching is a simple and standalone process whose purpose is clear. In contrast, it is relatively less comprehensible with rule [DK-INF-APP2](#) and the application judgment, where all three forms of the judgment (inference, checking, application) are mutually dependent.

SUBTYPING. DK shares the same subtyping relation as of OL. We thus omit the definition and use $\Psi \vdash^{DK} \sigma_1 <: \sigma_2$ to denote the subtyping relation in DK.

2.3.4 ALGORITHMIC TYPE SYSTEM

Dunfield and Krishnaswami [2013] also presented a sound and complete bidirectional algorithmic type system. The key idea of the algorithm is using *ordered* algorithmic contexts for storing existential variables and their solutions. Comparing to the algorithm for HM, they argued that their algorithm is remarkably simple. The algorithm is later discussed and used in [Chapter 4](#), [Chapter 5](#) and [Chapter 6](#). We will discuss more about it there.

PART II

TYPE INFERENCE

3 BIDIRECTIONAL TYPE CHECKING WITH THE APPLICATION MODE

3.1 INTRODUCTION

3.1.1 REVISITING BIDIRECTIONAL TYPE CHECKING

Traditional type checking rules can be heavyweight on annotations, in the sense that lambda-bound variables always need explicit annotations. As we have seen in Section 2.3, bidirectional type checking [Pierce and Turner 2000] provides an alternative, which allows types to propagate downward the syntax tree. For example, in the expression $(\lambda f : \text{Int} \rightarrow \text{Int}. f) (\lambda y. y)$, the type of y is provided by the type annotation on f . This is supported by the bidirectional typing rule [DK-INF-APP](#) for applications:

$$\frac{\text{DK-INF-APP} \quad \Psi \vdash^{DK} e_1 \Rightarrow \sigma \quad \Psi \vdash^{DK} \sigma \triangleright \sigma_1 \rightarrow \sigma_2 \quad \Psi \vdash^{DK} e_2 \Leftarrow \sigma_1}{\Psi \vdash^{DK} e_1 e_2 \Rightarrow \sigma_2}$$

Specifically, if we know that the type of e_1 is a function from $\sigma_1 \rightarrow \sigma_2$, we can check that e_2 has type σ_1 . Notice that here the type information flows from functions to arguments.

One guideline for designing bidirectional type checking rules [Dunfield and Pfenning 2004] is to distinguish introduction rules from elimination rules. Constructs which correspond to introduction forms are *checked* against a given type, while constructs corresponding to elimination forms *infer* (or synthesize) their types. For instance, under this design principle, the introduction rule for literals is supposed to be in checking mode, as in the rule [DK-CHK-INT](#):

$$\frac{\text{DK-CHK-INT}}{\Psi \vdash^{DK} n \Leftarrow \text{Int}}$$

Unfortunately, this means that the trivial program `1` cannot type-check, which in this case has to be rewritten to `1 : Int`.

In this particular case, bidirectional type checking goes against its original intention of removing burden from programmers, since a seemingly unnecessary annotation is needed. Therefore, in practice, bidirectional type systems do not strictly follow the guideline, and usually have additional inference rules for the introduction form of constructs. For literals, the corresponding rule is rule [DK-INF-INT](#).

$$\frac{\text{DK-INF-INT}}{\Psi \vdash^{DK} n \Rightarrow \text{Int}}$$

Now we can type check 1, but the price to pay is that two typing rules for literals are needed. Worse still, the same criticism applies to other constructs (e.g., pairs). This shows one drawback of bidirectional type checking: often to minimize annotations, many rules are duplicated for having both inference and checking mode, which scales up with the typing rules in a type system.

3.1.2 TYPE CHECKING WITH THE APPLICATION MODE

We propose a variant of bidirectional type checking with a new *application mode* (unrelated to the application judgment in DK). The application mode preserves the advantage of bidirectional type checking, namely many redundant annotations are removed, while certain programs can type check with even fewer annotations. Also, with our proposal, the inference mode is a special case of the application mode, so it does not produce duplications of rules in the type system. Additionally, the checking mode can still be *easily* combined into the system. The essential idea of the application mode is to enable the type information flow in applications to propagate from arguments to functions (instead of from functions to arguments as in traditional bidirectional type checking).

To motivate the design of bidirectional type checking with an application mode, consider the simple expression

$$(\lambda x. x) 1$$

This expression cannot type check in traditional bidirectional type checking, because unannotated abstractions, as a construct which correspond to introduction forms, only have a checking mode, so annotations are required¹. For example,

$$((\lambda x. x) : \text{Int} \rightarrow \text{Int}) 1$$

¹It type-checks in DK, because in DK rules for lambdas are duplicated for having both inference (integrated with type inference techniques) and checking mode.

In this example we can observe that if the type of the argument is accounted for in inferring the type of $\lambda x. x$, then it is actually possible to deduce that the lambda expression has type $\text{Int} \rightarrow \text{Int}$, from the argument 1.

THE APPLICATION MODE. If types flow from the arguments to the function, an alternative idea is to push the type of the arguments into the typing of the function, as follows,

$$\frac{\text{APP} \quad \Psi \vdash e_2 \Rightarrow \sigma_1 \quad \Psi; \Sigma, \sigma_1 \vdash e_1 \Rightarrow \sigma \rightarrow B}{\Psi; \Sigma \vdash e_1 e_2 \Rightarrow B}$$

In this rule, there are two kinds of judgments. The first judgment is just the usual inference mode, which is used to infer the type of the argument e_2 . The second judgment, the application mode, is similar to the inference mode, but it has an additional context Σ . The context Σ is a stack that tracks the types of the arguments of outer applications. In the rule for application, the type of the argument e_2 synthesizes its type σ_1 , which then is pushed into the application context Σ for inferring the type of e_1 . Applications are themselves in the application mode, since they can be in the context of an outer application.

Lambda expressions can now make use of the application context, leading to the following rule:

$$\frac{\text{LAM} \quad \Psi, x : \sigma; \Sigma \vdash e \Rightarrow B}{\Psi; \Sigma, \sigma \vdash \lambda x. e \Rightarrow \sigma \rightarrow B}$$

The type σ that appears last in the application context serves as the type for x , and type checking continues with a smaller application context and $x : \sigma$ in the typing context. Therefore, using the rule [APP](#) and rule [LAM](#), the expression $(\lambda x. x) 1$ can type-check without annotations, since the type Int of the argument 1 is used as the type of the binding x .

Note that, since the examples so far are based on simple types, obviously they can be solved by integrating type inference and relying on techniques like unification or constraint solving (as in DK). However, here the point is that the application mode helps to reduce the number of annotations *without requiring such sophisticated techniques*. Also, the application mode helps with situations where those techniques cannot be easily applied, such as type systems with subtyping.

INTERPRETATION OF THE APPLICATION MODE. As we have seen, the guideline for designing bi-directional type checking [Dunfield and Pfenning 2004], based on introduction and

elimination rules, is often not enough in practice. This leads to extra introduction rules in the inference mode. The application mode does not distinguish between introduction rules and elimination rules. Instead, to decide whether a rule should be in inference or application mode, we need to think whether the expression can be applied or not. Variables, lambda expressions and applications are all examples of expressions that can be applied, and they should have application mode rules. However literals or pairs cannot be applied and should have inference rules. For example, type checking pairs would simply have the inference mode. Nevertheless elimination rules of pairs could have non-empty application contexts (see Section ?? for details). In the application mode, arguments are always inferred first in applications and propagated through application contexts. An empty application context means that an expression is not being applied to anything, which allows us to model the inference mode as a particular case².

PARTIAL TYPE CHECKING. The inference mode synthesizes the type of an expression, and the checked mode checks an expression against some type. A natural question is how do these modes compare to application mode. An answer is that, in some sense: the application mode is stronger than inference mode, but weaker than checked mode. Specifically, the inference mode means that we know nothing about the type an expression before hand. The checked mode means that the whole type of the expression is already known before hand. With the application mode we know some partial type information about the type of an expression: we know some of its argument types (since it must be a function type when the application context is non-empty), but not the return type.

Instead of nothing or all, this partialness gives us a finer grain notion on how much we know about the type of an expression. For example, assume $e : \sigma_1 \rightarrow \sigma_2 \rightarrow \sigma_3$. In the inference mode, we only have e . In the checked mode, we have both e and $\sigma_1 \rightarrow \sigma_2 \rightarrow \sigma_3$. In the application mode, we have e , and maybe an empty context (which degenerates into inference mode), or an application context σ_1 (we know the type of first argument), or an application context σ_1, σ_2 (we know the types of both arguments).

TRADE-OFFS. Note that the application mode is *not* conservative over traditional bidirectional type checking due to the different information flow. However, it provides a new design choice for type inference/checking algorithms, especially for those where the information about arguments is useful. Therefore we next discuss some benefits of the application mode

²Although the application mode generalizes the inference mode, we refer to them as two different modes. Thus the variant of bi-directional type checking in this paper is interpreted as a type system with both *inference* and *application* modes.

for two interesting cases where functions are either variables; or lambda (or type) abstractions.

3.1.3 BENEFITS OF INFORMATION FLOWING FROM ARGUMENTS TO FUNCTIONS

LOCAL CONSTRAINT SOLVER FOR FUNCTION VARIABLES. Many type systems, including type systems with *implicit polymorphism* and/or *static overloading*, need information about the types of the arguments when type checking function variables. For example, in conventional functional languages with implicit polymorphism, function calls such as (id 1) where $\text{id} : \forall a. (a \rightarrow a)$, are *pervasive*. In such a function call the type system must instantiate a to Int . Dealing with such implicit instantiation gets trickier in systems with *higher-ranked types*. For example, Jones et al. [2007] require additional syntactic forms and relations, whereas DK add a special purpose matching or the application judgment.

With the application mode, all the type information about the arguments being applied is available in application contexts and can be used to solve instantiation constraints. To exploit such information, the type system employs a special subtyping judgment called *application subtyping*, with the form $\Sigma \vdash \sigma_1 <: \sigma_2$. Unlike conventional subtyping, computationally Ψ and σ_1 are interpreted as inputs and σ_2 as output. In above example, we have that $\text{Int} \vdash \forall a. a \rightarrow a <: \sigma$ and we can determine that $a = \text{Int}$ and $\sigma = \text{Int} \rightarrow \text{Int}$. In this way, type system is able to solve the constraints *locally* according to the application contexts since we no longer need to propagate the instantiation constraints to the typing process.

DECLARATION DESUGARING FOR LAMBDA ABSTRACTIONS. An interesting consequence of the usage of an application mode is that it enables the following **let** sugar:

$$\text{let } x = e_1 \text{ in } e_2 \rightsquigarrow (\lambda x. e_2) e_1$$

Such syntactic sugar for **let** is, of course, standard. However, in the context of implementations of typed languages it normally requires extra type annotations or a more sophisticated type-directed translation. Type checking $(\lambda x. e_2) e_1$ would normally require annotations (for example an annotation for x), or otherwise such annotation should be inferred first. Nevertheless, with the application mode no extra annotations/inference is required, since from the type of the argument e_1 it is possible to deduce the type of x . Generally speaking, with the application mode *annotations are never needed for applied lambdas*. Thus **let** can be the usual sugar from the untyped lambda calculus, including HM-style **let** expression and even type declarations.

4 UNIFICATION WITH PROMOTION

PART III

EXTENSIONS

5 HIGHER RANK GRADUAL TYPES

6

DEPENDENT TYPES

PART IV

RELATED AND FUTURE WORK

7 RELATED WORK

8 FUTURE WORK

PART V

EPILOGUE

9 CONCLUSION

BIBLIOGRAPHY

[Citing pages are listed after each reference.]

- Amal Ahmed, Robert Bruce Findler, Jacob Matthews, and Philip Wadler. 2009. Blame for All. In *Proceedings for the 1st Workshop on Script to Program Evolution (STOP '09)*. Association for Computing Machinery, New York, NY, USA, 1–13. <https://doi.org/10.1145/1570506.1570507> [cited on page 4]
- Andrea Asperti, Wilmer Ricciotti, Claudio Sacerdoti Coen, and Enrico Tassi. 2012. A Bi-Directional Refinement Algorithm for the Calculus of (Co) Inductive Constructions. *Logical Methods in Computer Science* 8 (2012), 1–49. [cited on page 14]
- Thierry Coquand. 1996. An algorithm for type-checking dependent types. *Science of Computer Programming* 26, 1-3 (1996), 167–177. [cited on page 14]
- Luis Damas and Robin Milner. 1982. Principal Type-Schemes for Functional Programs. In *Proceedings of the 9th ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages (POPL '82)*. Association for Computing Machinery, New York, NY, USA, 207–212. <https://doi.org/10.1145/582153.582176> [cited on pages 7 and 10]
- Rowan Davies and Frank Pfenning. 2000. Intersection Types and Computational Effects. In *Proceedings of the Fifth ACM SIGPLAN International Conference on Functional Programming (ICFP '00)*. Association for Computing Machinery, New York, NY, USA, 198–208. <https://doi.org/10.1145/351240.351259> [cited on page 14]
- Joshua Dunfield and Neelakantan R. Krishnaswami. 2013. Complete and Easy Bidirectional Typechecking for Higher-Rank Polymorphism. In *Proceedings of the 18th ACM SIGPLAN International Conference on Functional Programming (ICFP '13)*. Association for Computing Machinery, New York, NY, USA, 429–442. <https://doi.org/10.1145/2500365.2500582> [cited on pages 14, 17, and 18]
- Joshua Dunfield and Frank Pfenning. 2004. Tridirectional Typechecking. *SIGPLAN Not.* 39, 1 (Jan. 2004), 281–292. <https://doi.org/10.1145/982962.964025> [cited on pages 14, 21, and 23]

- Ronald Garcia and Matteo Cimini. 2015. Principal Type Schemes for Gradual Programs. In *Proceedings of the 42nd Annual ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages (POPL '15)*. Association for Computing Machinery, New York, NY, USA, 303–315. <https://doi.org/10.1145/2676726.2676992> [cited on page 4]
- J. Roger Hindley. 1969. The Principal Type-Scheme of an Object in Combinatory Logic. *Trans. Amer. Math. Soc.* 146 (1969), 29–60. [cited on page 7]
- Simon Peyton Jones, Dimitrios Vytiniotis, Stephanie Weirich, and Mark Shields. 2007. Practical type inference for arbitrary-rank types. *Journal of functional programming* 17, 1 (2007), 1–82. [cited on pages 10, 14, and 25]
- Assaf J Kfoury and Jerzy Tiuryn. 1992. Type reconstruction in finite rank fragments of the second-order λ -calculus. *Information and computation* 98, 2 (1992), 228–257. [cited on page 10]
- Andres Löh, Conor McBride, and Wouter Swierstra. 2010. A tutorial implementation of a dependently typed lambda calculus. *Fundamenta informaticae* 102, 2 (2010), 177–207. [cited on page 14]
- Robin Milner. 1978. A theory of type polymorphism in programming. *Journal of computer and system sciences* 17, 3 (1978), 348–375. [cited on page 7]
- Martin Odersky and Konstantin Läuffer. 1996. Putting Type Annotations to Work. In *Proceedings of the 23rd ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages (POPL '96)*. Association for Computing Machinery, New York, NY, USA, 54–67. <https://doi.org/10.1145/237721.237729> [cited on pages 7, 10, and 11]
- Benjamin C. Pierce and David N. Turner. 2000. Local Type Inference. *ACM Trans. Program. Lang. Syst.* 22, 1 (Jan. 2000), 1–44. <https://doi.org/10.1145/345099.345100> [cited on pages 14 and 21]
- Jeremy Siek and Walid Taha. 2007. Gradual Typing for Objects. In *Proceedings of the 21st European Conference on Object-Oriented Programming (ECOOP'07)*. Springer-Verlag, Berlin, Heidelberg, 2–27. [cited on page 4]
- Jeremy G Siek, Michael M Vitousek, Matteo Cimini, and John Tang Boyland. 2015. Refined criteria for gradual typing. In *1st Summit on Advances in Programming Languages (SNAPL 2015)*. Schloss Dagstuhl-Leibniz-Zentrum fuer Informatik. [cited on page 4]

- Joe B Wells. 1999. Typability and Type Checking in System F are Equivalent and Undecidable. *Annals of Pure and Applied Logic* 98, 1-3 (1999), 111–156. [cited on page 13]
- Hongwei Xi and Frank Pfenning. 1999. Dependent Types in Practical Programming. In *Proceedings of the 26th ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages (POPL '99)*. Association for Computing Machinery, New York, NY, USA, 214–227. <https://doi.org/10.1145/292540.292560> [cited on page 14]
- Ningning Xie, Xuan Bi, and Bruno C d S Oliveira. 2018. Consistent Subtyping for All. In *European Symposium on Programming*. Springer, 3–30. [cited on page 5]
- Ningning Xie, Xuan Bi, Bruno C. D. S. Oliveira, and Tom Schrijvers. 2019a. Consistent Subtyping for All. *ACM Transactions on Programming Languages and Systems* 42, 1, Article 2 (Nov. 2019), 79 pages. <https://doi.org/10.1145/3310339> [cited on page 5]
- Ningning Xie, Richard A. Eisenberg, and Bruno C. d. S. Oliveira. 2019b. Kind Inference for Datatypes. *Proc. ACM Program. Lang.* 4, POPL, Article 53 (Dec. 2019), 28 pages. <https://doi.org/10.1145/3371121> [cited on page 5]
- Ningning Xie and Bruno C d S Oliveira. 2017. Towards Unification for Dependent Types. In *Draft Proceedings of the 18th Symposium on Trends in Functional Programming (TFP '18)*. Extended abstract. [cited on page 5]
- Ningning Xie and Bruno C d S Oliveira. 2018. Let Arguments Go First. In *European Symposium on Programming*. Springer, 272–299. [cited on page 5]

PART VI

TECHNICAL APPENDIX

