Extensional Equality in Intensional Type Theory

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Abstract

We present a new approach to introducing an extensional propositional equality in Intensional Type Theory. Our construction is based on the observation that there is a sound, intensional setoid model in Intensional Type theory with a proof-irrelevant universe of propositions and η-rules for Π- and Σ-types. The Type Theory corresponding to this model is decidable, has no irreducible constants and permits large eliminations, which are essential for universes.
***Keywords.** Type Theory, categorical models.*

1. Introduction and Summary

In Intensional Type Theory (see e.g. [11]) we differentiate between a decidable definitional equality (which we denote by $=$) and a propositional equality type ($\mathrm{Id}_\sigma(-,-)$) for any given type σ) which requires proof. Typing only depends on definitional equality and hence is decidable.

In Intensional Type Theory the type corresponding to the principle of extensionality

$$\mathrm{Ext}_{x \in \sigma, \tau(x)} \equiv \Pi_{f,g \in (\Pi x \in \sigma, \tau(x))} \\ (\Pi_{x \in \sigma} \mathrm{Id}_{\tau(x)}(f(x), g(x))) \\ \to \mathrm{Id}_{\Pi x \in \sigma, \tau(x)}(f, g)$$

is not inhabited. To see this let $\sigma = \tau = \mathrm{Nat}$ and $f = \lambda x \in \mathrm{Nat}.x$, $g = \lambda x \in \mathrm{Nat}.x + 0$, where addition is defined s.t. $x \neq x + 0$. Using Nat-elimination we can show that $\Pi_{x \in \mathrm{Nat}} \mathrm{Id}_{\mathrm{Nat}}(f(x), g(x))$ is inhabited but $\mathrm{Id}_{\mathrm{Nat} \to \mathrm{Nat}}(f, g)$ is not, because f and g have different normal forms.

It has been an open problem how to extend Intensional Type Theory s.t. Ext is inhabited without destroying other fundamental properties. Ext is provable in Extensional Type Theory [10], where propositional and definitional equality are identified, but then equality and type checking become undecidable. We may introduce a constant of type Ext but then, using the elimination constant for Id, we can also define irreducible terms at other types (like Nat). We say that such a theory is not *adequate* because we can construct closed terms of type Nat which are not reducible to numerals.

The problem of extensionality in Intensional Type Theory has been extensively studied by Martin Hofmann [5]. His basic insight is that extensional equality can be modeled by an *intensional model construction* such as the setoid model, where every closed type is interpreted by a type and an equivalence relation. However, a naive version of the setoid model does not work because it does not satisfy all the required definitional equalities. In [6] Hofmann presents a solution using a modified interpretation of families. Unfortunately, this approach does not allow definitions of sets or propositions by recursion (large eliminations), in particular this prohibits the introduction of universes.

Our solution is also based on the setoid model but as the metatheory, where the construction takes place, we use an extension of Intensional Type Theory by a universe of propositions **Prop**, such that all proofs of a proposition are definitionally equal. Moreover, we assume that the η-rules for Π-types and Σ-types (surjective pairing) hold in the metatheory. We show that this extension of Intensional Type Theory is decidable. Inside our metatheory we define an intensional model which corresponds to a Type Theory – the object theory – with the following properties:

1. Definitional equality (and hence typechecking) is decidable.

2. Ext is inhabited.

3. The theory is adequate, i.e. all closed natural numbers are definitionally equal to numerals.

4. Large eliminations (e.g. a simply typed universe) can be interpreted.

Extensional Concepts In Intensional Type Theory

Shahid Rahman,Zoe McConaughey,Ansten Klev,Nicolas Clerbout

Extensional Concepts In Intensional Type Theory:

Extensional Concepts in Intensional Type Theory Martin Hofmann,1995 Theories of dependent types have been proposed as a foundation of constructive mathematics and as a framework in which to construct certified programs In these applications an important role is played by identity types which internalise equality and therefore are essential for accommodating proofs and programs in the same formal system This thesis attempts to reconcile the two different ways that type theories deal with identity types In extensional type theory the propositional equality induced by the identity types is identified with definitional equality i e conversion This renders type checking and well formedness of propositions undecidable and leads to non termination in the presence of universes In intensional type theory propositional equality is coarser than definitional equality the latter being confined to definitional expansion and normalisation Then type checking and well formedness are decidable and this variant is therefore adopted by most implementations However the identity type in intensional type theory is not powerful enough for formalisation of mathematics and program development Notably it does not identify pointwise equal functions functional extensionality and provides no means of redefining equality on a type as a given relation i e quotient types We call such capabilities extensional concepts Other extensional concepts of interest are uniqueness of proofs and more specifically of equality proofs subset types and propositional extensionality the identification of equivalent propositions In this work we investigate to what extent these extensional concepts may be added to intensional type theory without sacrificing decidability and existence of canonical forms The method we use is the translation of identity types into equivalence relations defined by induction on the type structure In this way type theory with extensional concepts can be understood as a high level language for working with equivalence relations instead of equality Such translations of type theory into itself turn out to be best described using categorical models of type theory We thus begin with a thorough treatment of categorical models with particular emphasis on the interpretation of type theoretic syntax in such models We then show how pairs of types and predicates can be organised into a model of type theory in which subset types are available and in which any two proofs of a proposition are equal This model has applications in the areas of program extraction from proofs and modules for functional programs For us its main purpose is to clarify the idea of syntactic translations via categorical model constructions The main result of the thesis consists of the construction of two models in which functional extensionality and quotient types are available In the first one types are modelled by types together with proposition valued partial equivalence relations This model is rather simple and in addition provides subset types and propositional extensionality However it does not furnish proper dependent types such as vectors or matrices We try to overcome this disadvantage by using another model based on families of type valued equivalence relations which is however much more complicated and validates certain conversion rules only up to propositional equality We illustrate the use of these models by several small examples taken from both formalised mathematics and program development We also establish various

syntactic properties of propositional equality including a proof of the undecidability of typing in extensional type theory and a correspondence between derivations in extensional type theory and terms in intensional type theory with extensional concepts added Furthermore we settle affirmatively the hitherto open question of the independence of unicity of equality proofs in intensional type theory which implies that the addition of pattern matching to intensional type theory does not yield a conservative extension **Extensional Constructs in Intensional Type Theory** Martin Hofmann,2012-12-06 Extensional Constructs in Intensional Type Theory presents a novel approach to the treatment of equality in Martin Loef type theory a basis for important work in mechanised mathematics and program verification Martin Hofmann attempts to reconcile the two different ways that type theories deal with identity types The book will be of interest particularly to researchers with mainly theoretical interests and implementors of type theory based proof assistants and also fourth year undergraduates who will find it useful as part of an advanced course on type theory *Treatise on Intuitionistic Type Theory* Johan Georg Granström,2011-06-02 Intuitionistic type theory can be described somewhat boldly as a partial fulfillment of the dream of a universal language for science This book expounds several aspects of intuitionistic type theory such as the notion of set reference vs computation assumption and substitution Moreover the book includes philosophically relevant sections on the principle of compositionality lingua characteristica epistemology propositional logic intuitionism and the law of excluded middle Ample historical references are given throughout the book Types for Proofs and Programs Paul Callaghan,Zhaohui Luo,James McKinna,Robert Pollack,2002-02-20 This book constitutes the thoroughly refereed post proceedings of the International Workshop of the TYPES Working Group TYPES 2000 held in Durham UK in December 2000 The 15 revised full papers presented were carefully reviewed and selected during two rounds of refereeing and revision All current issues on type theory and type systems and their applications to programming systems design and proof theory are addressed *Types for Proofs and Programs* Stefano Berardi,Mario Coppo,1996-10-02 This volume contains a refereed selection of revised full papers chosen from the contributions presented during the Third Annual Workshop held under the auspices of the ESPRIT Basic Research Action 6453 Types for Proofs and Programs The workshop took place in Torino Italy in June 1995 Type theory is a formalism in which theorems and proofs specifications and programs can be represented in a uniform way The 19 papers included in the book deal with foundations of type theory logical frameworks and implementations and applications all in all they constitute a state of the art survey for the area of type theory **Types for Proofs and Programs** Hendrik Pieter Barendregt,Tobias Nipkow,1994-05-20 This volume contains thoroughly refereed and revised full papers selected from the presentations at the first workshop held under the auspices of the ESPRIT Basic Research Action 6453 Types for Proofs and Programs in Nijmegen The Netherlands in May 1993 As the whole ESPRIT BRA 6453 this volume is devoted to the theoretical foundations design and applications of systems for theory development Such systems help in designing mathematical axiomatisation performing computer aided logical reasoning and managing databases of

mathematical facts they are also known as proof assistants or proof checkers   Categorical Logic and Type Theory B. Jacobs,2001-05-10 This book is an attempt to give a systematic presentation of both logic and type theory from a categorical perspective using the unifying concept of fibred category Its intended audience consists of logicians type theorists category theorists and theoretical computer scientists   *Homotopy Type Theory: Univalent Foundations of Mathematics* ,   Types for Proofs and Programs Jean-Christophe Filliatre,2006-01-25 The 17 revised full papers presented here cover all current issues of formal reasoning and computer programming based on type theory are addressed in particular languages and computerised tools for reasoning and applications in several domains such as analysis of programming languages certified software formalisation of mathematics and mathematics education   *Theorem Proving in Higher Order Logics* Konrad Slind,Annette Bunker,Ganesh C. Gopalakrishnan,2004-09-01 This volume constitutes the proceedings of the 17th International Conference on Theorem Proving in Higher Order Logics TPHOLs 2004 held September 14 17 2004 in Park City Utah USA TPHOLs covers all aspects of theorem proving in higher order logics as well as related topics in theorem proving and veri cation There were 42 papers submitted to TPHOLs 2004 in the full research ca gory each of which was refereed by at least 3 reviewers selected by the program committee Of these submissions 21 were accepted for presentation at the c ference and publication in this volume In keeping with longstanding tradition TPHOLs 2004 also o ered a venue for the presentation of work in progress where researchers invited discussion by means of a brief introductory talk and then discussed their work at a poster session A supplementary proceedings c taining papers about in progress work was published as a 2004 technical report of the School of Computing at the University of Utah The organizers are grateful to Al Davis Thomas Hales and Ken McMillan for agreeing to give invited talks at TPHOLs 2004 The TPHOLs conference traditionally changes continents each year in order to maximize the chances that researchers from around the world can attend   **Types for Proofs and Programs** Herman Geuvers,Freek Wiedijk,2003-04-28 This book constitutes the thoroughly refereed post proceedings of the Second International Workshop of the TYPES Working Group TYPES 2002 held in Berg en Dal The Netherlands in April 2002 The 18 revised full papers presented were carefully selected during two rounds of reviewing and improvement All current issues in type theory and type systems and their applications to programming systems design and proof theory are addressed Among the systems dealt with are Coq and Isar HOL   **Intensional Logic and Logical Grammar** L.T.F. Gamut,2024-05-31 Although the two volumes of Logic Language and Meaning can be used independently of one another together they provide a comprehensive overview of modern logic as it is used as a tool in the analysis of natural language Both volumes provide exercises and their solutions   **Foundations of Software Science and Computation Structures** Stefan Kiefer,Christine Tasson,2021-03-22 This open access book constitutes the proceedings of the 24th International Conference on Foundations of Software Science and Computational Structures FOSSACS 2021 which was held during March 27 until April 1 2021 as part of the European Joint Conferences on Theory and Practice of Software ETAPS

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Semantics and Logics of Computation Andrew M. Pitts,P. Dybjer,1997-01-30 The aim of this volume is to present modern developments in semantics and logics of computation in a way that is accessible to graduate students The book is based on a summer school at the Isaac Newton Institute and consists of a sequence of linked lecture course by international authorities in the area The whole set have been edited to form a coherent introduction to these topics most of which have not been presented pedagogically before   Theorem Proving in Higher Order Logics Victor A. Carreno,Cesar A. Munoz,Sofiene Tahar,2003-08-02 This book constitutes the refereed proceedings of the 15th International Conference on Theorem Proving in Higher Order Logics TPHOLs 2002 held in Hampton VA USA in August 2002 The 20 revised full papers presented together with 2 invited contributions were carefully reviewed and selected from 34 submissions All current issues in HOL theorem proving and formal verification of software and hardware systems are addressed Among the HOL theorem proving systems evaluated are Isabelle HOL Isabelle Isar and Coq   *Immanent Reasoning or Equality in Action* Shahid Rahman,Zoe McConaughey,Ansten Klev,Nicolas Clerbout,2018-08-16 This monograph proposes a new way of implementing interaction in logic It also provides an elementary introduction to Constructive Type Theory CTT The authors equally emphasize basic ideas and finer technical details In addition many worked out exercises and examples will help readers to better understand the concepts under discussion One of the chief ideas animating this study is that the dialogical understanding of definitional

equality and its execution provide both a simple and a direct way of implementing the CTT approach within a game theoretical conception of meaning In addition the importance of the play level over the strategy level is stressed binding together the matter of execution with that of equality and the finitary perspective on games constituting meaning According to this perspective the emergence of concepts are not only games of giving and asking for reasons games involving Why questions they are also games that include moves establishing how it is that the reasons brought forward accomplish their explicative task Thus immanent reasoning games are dialogical games of Why and How **Theorem Proving in Higher Order Logics** Joe Hurd,2005-08-08 This book constitutes the refereed proceedings of the 18th International Conference on Theorem Proving in Higher Order Logics TPHOLs 2005 held in Oxford UK in August 2005 The 20 revised full papers presented together with 2 invited papers and 4 proof pearls concise and elegant presentations of interesting examples were carefully reviewed and selected from 49 submissions All current issues in HOL theorem proving and formal verification of software and hardware systems are addressed Among the topics of this volume are theorem proving verification recursion and induction mechanized proofs mathematical logic proof theory type systems program verification and proving systems like HOL Coq ACL2 Isabelle HOL and Isabelle HOLCF **Index to Theses with Abstracts Accepted for Higher Degrees by the Universities of Great Britain and Ireland and the Council for National Academic Awards** ,1996 Theses on any subject submitted by the academic libraries in the UK and Ireland

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