

Abstract. I prove that a λ -term that has a negatively non-duplicated typing is always $\beta\eta$ -equal to an almost affine λ -term.

Keywords: almost affine lambda term, negatively non-duplicated sequent

1. Introduction

A λ -term is *affine* if no subterm contains more than one free occurrence of the same variable. It is known that an affine λ -term is always typable [6] and its principal typing is *balanced* in the sense that each atomic type occurs positively at most once and negatively at most once¹ [4, 8]. Also, a balanced sequent can have at most one inhabitant up to $\beta\eta$ -equality. This is known as the *Coherence Theorem* [15, 16, 3]. It follows that up to $\beta\eta$ -equality, an affine λ -term is uniquely characterized by its principal typing. An additional important property of balanced sequents is that a β -normal inhabitant of a balanced sequent is always affine. A slightly weaker result of Jaśkowski [9] states that a balanced sequent that is provable in intuitionistic logic has an affine inhabitant, which, together with the Coherence Theorem, implies the stronger statement. A direct proof was also provided by Hirokawa [8]. So there is a bijective correspondence between the affine λ -terms in long normal form and the balanced sequents that are provable in intuitionistic logic.

Previously, I introduced the notions of *almost affine* and *almost linear* λ -terms in order to isolate a computationally tractable class of “context-free grammars on λ -terms” [10, 12], and subsequently used them to capture tree transductions that are definable in monadic second-order logic in terms of “higher-order” homomorphisms [11]. A λ -term is almost affine if it is typable and has a typing where any variable that occurs free more than once in any subterm has an atomic type. A λ -term is almost linear if it is an almost affine λI -term. An almost affine λ -term corresponds to a derivation in sequent calculus where the structural rule of contraction is restricted to atomic formulas [1]. A sequent is called *negatively non-duplicated* if each atomic type occurs negatively at most once. Aoto and Ono [2] proved that

¹This definition of “balanced” is from Mints [16]. Babaev and Sol’ev [3] and Hirokawa [8] use “balanced” in the weaker sense of containing at most two occurrences of each atomic type.

all inhabitants of a negatively non-duplicated sequent are $\beta\eta$ -equal, generalizing the Coherence Theorem. Aoto [1] proved that a minimal intuitionistically provable sequent that has an almost affine inhabitant must be negatively non-duplicated. This was slightly generalized in [10, 12], where it was proved that a principal typing of an almost affine λ -term is negatively non-duplicated. Thus, almost affine λ -terms are also characterized by their principal typing up to $\beta\eta$ -equality.

In this paper, I prove an analogue of the theorem of Jaśkowski [9] and Hirokawa [8] for negatively non-duplicated sequents: any inhabitant of a negatively non-duplicated sequent is $\beta\eta$ -equal to an almost affine λ -term.² In the course of this proof, I also derive Aoto and Ono's [2] theorem as an immediate corollary.

A consequence of the main theorem of this paper is that a λ -term M in long normal form β -expands to an almost affine λ -term if and only if the principal typing of M is negatively non-duplicated. This is a useful characterization, since the class of almost affine λ -terms is not closed under β -reduction and we do not have an equally simple, purely syntactic characterization of the long normal forms of almost affine λ -terms.³

2. Simply Typed Lambda Calculus

2.1. Lambda Terms

This and the next subsections fix terminology and notations. We mostly follow [7].

We assume we are given a set \mathcal{X} of *variables*, of which there are countably many. The set Λ of (*pure*) λ -terms is the smallest superset of \mathcal{X} such that $M \in \Lambda$ and $N \in \Lambda$ imply $(MN) \in \Lambda$, and $x \in \mathcal{X}$ and $M \in \Lambda$ imply $(\lambda x.M) \in \Lambda$. As usual, we allow ourselves to omit the outermost pair of parentheses, and write MNP for $(MN)P$ and $\lambda x_1 \dots x_n.M$ for $\lambda x_1.(\dots(\lambda x_n.M)\dots)$.

It is best to be precise about α -equivalence. We use strings over $\{0, 1\}$ to refer to *positions* inside a λ -term. We write ϵ for the empty string,

²This result was stated without proof in [12] and mentioned in [13].

³Bourreau and Salvati [5] characterized λ -terms that are in long normal form relative to a negatively non-duplicated typing in terms of the notion of *first-order copying* λ -term. They used game semantics to obtain this characterization (among other results), but the characterization can also be obtained from the results in section 3 of this paper fairly easily. Bourreau and Salvati made no attempt to show that a first-order copying λ -term always β -expands to an almost affine λ -term.

and write $u \leq v$ to mean u is a prefix of v . Given a λ -term M , the set of *positions* of M , written $\text{pos}(M)$, is defined by $\text{pos}(x) = \{\epsilon\}$ for $x \in \mathcal{X}$, $\text{pos}(MN) = \{\epsilon\} \cup \{0u \mid u \in \text{pos}(M)\} \cup \{1u \mid u \in \text{pos}(N)\}$, and $\text{pos}(\lambda x.M) = \{\epsilon\} \cup \{0u \mid u \in \text{pos}(M)\}$.

If u is a position of M , the *subterm* of M occurring at u , written M/u , is defined by $M/\epsilon = M$, $(MN)/0u = M/u$, $(MN)/1u = N/u$, and $(\lambda x.M)/0u = M/u$. Suppose $M/u = x \in \mathcal{X}$. The occurrence of x at u in M is called *free* if there is no prefix v of u such that M/v is of the form $\lambda x.N$. Otherwise, the occurrence of x at u is *bound* by the longest prefix v of u such that M/v is of the form $\lambda x.N$, in which case v is called the *binder* of u . The *binding map* b_M of M is a partial function from $\text{pos}(M)$ to $\text{pos}(M)$ such that $b_M(u) = v$ holds if and only if v is the binder of u . We write $\text{FV}(M)$ for the set of variables that have free occurrences in M .

Let M, N be λ -terms. We say that M and N are α -*equivalent* and write $M \equiv_\alpha N$ if $\text{pos}(M) = \text{pos}(N)$, $b_M = b_N$, and for all $u \in \text{pos}(M) - \text{dom}(b_M)$, $M/u \in \mathcal{X}$ implies $M/u = N/u$. One can readily check that \equiv_α is an equivalence relation.

A λ -term M is *regular* [14] if for each $x \in \mathcal{X}$, there is at most one $u \in \text{pos}(M)$ such that M/u is of the form $\lambda x.N$, and if there is one, there is no free occurrence of x in M . For every λ -term M , there is a regular M' such that $M \equiv_\alpha M'$.

Let M, N be λ -terms and x be a variable. We say that N is *free for x in M* if for all $y \in \text{FV}(N)$ and for all $u \in \text{pos}(M)$ such that x occurs free at u , there is no $v \leq u$ such that M/v is of the form $\lambda y.R$. When N is free for x in M , the result of *substituting N for x in M* , written $M[x := N]$, is the λ -term that results from replacing all free occurrences of x in M by N .

An occurrence of a λ -term of the form $(\lambda x.M)N$ inside a λ -term is called a β -*redex*. Note that whenever $(\lambda x.M)N$ occurs in a regular λ -term, N is free for x in M , and consequently $M[x := N]$ is defined.

We write $P \rightarrow_\beta Q$ when there are λ -terms P' and Q' such that $P \equiv_\alpha P'$, $Q' \equiv_\alpha Q$, P' is regular, and Q' is the result of replacing a β -redex $(\lambda x.M)N$ in P' by $M[x := N]$. We write $P \twoheadrightarrow_\beta Q$ to mean either $P \equiv_\alpha Q$ or P is related to Q by the transitive closure of the relation \rightarrow_β . When $P \twoheadrightarrow_\beta Q$, we say that P β -*reduces* to Q and Q β -*expands* to P . A λ -term P is in β -*normal form* if it does not contain any β -redexes.

An occurrence of a λ -term of the form $\lambda x.Mx$ with $x \notin \text{FV}(M)$ inside a λ -term is called an η -*redex*. We write $P \rightarrow_\eta Q$ when there are P', Q' such that $P \equiv_\alpha P'$, $Q' \equiv_\alpha Q$, and Q' is the result of replacing an η -redex $\lambda x.Mx$ in P' by M . We use \twoheadrightarrow_η in a similar way to \twoheadrightarrow_β . When $P \twoheadrightarrow_\eta Q$, we say that P η -*reduces* to Q and Q η -*expands* to P . We write $P =_{\beta\eta} Q$ (read:

P is $\beta\eta$ -equal to Q) when P and Q are related by the symmetric transitive closure of the relation $\rightarrow_\beta \cup \rightarrow_\eta$.

2.2. Type Assignment System

We write At for the set of atomic types, which we assume to be countably infinite. The set of *types* is the smallest superset \mathcal{T} of At such that $\alpha \in \mathcal{T}$ and $\beta \in \mathcal{T}$ imply $(\alpha \rightarrow \beta) \in \mathcal{T}$. As usual, we omit the outermost pair of parentheses when writing types, and we write $\alpha \rightarrow \beta \rightarrow \gamma$ for $\alpha \rightarrow (\beta \rightarrow \gamma)$.

The set of *positions* of a type α , written $\text{pos}(\alpha)$, is defined by $\text{pos}(p) = \{\epsilon\}$ for $p \in At$ and $\text{pos}(\alpha \rightarrow \beta) = \{\epsilon\} \cup \{1u \mid u \in \text{pos}(\alpha)\} \cup \{0u \mid u \in \text{pos}(\beta)\}$. A position u is *positive* if its parity (i.e., the number of 1s in u modulo 2) is 0, and *negative* if its parity is 1.

If u is a position of α , the *subtype* of α occurring at u , written α/u , is defined by $\alpha/\epsilon = \alpha$, $(\alpha \rightarrow \beta)/0u = \beta/u$, $(\alpha \rightarrow \beta)/1u = \alpha/u$. If $\alpha/u = \beta$, we say that β occurs at position u in α , and the occurrence of β at position u is *positive* (resp. *negative*) if u is positive (resp. negative). If β has a positive (resp. negative) occurrence in α , we say that β *occurs positively* (resp. *negatively*) in α .

An occurrence of β at position u in α is a *subpremise* if $u = u'1$ for some u' . Such an occurrence is a *positive* (resp. *negative*) *subpremise* if it is a positive (resp. negative) occurrence. We also say that β is a positive (negative) subpremise of α if β occurs as a positive (negative) subpremise in α , and write $\text{Possub}(\alpha)$ and $\text{Negsub}(\alpha)$ for the set of types that are positive and negative subpremises of α , respectively.

The *tail* of a type $\alpha = \alpha_1 \rightarrow \cdots \rightarrow \alpha_n \rightarrow p$, written $\text{tail}(\alpha)$, is p . Note that if $u \in \text{pos}(\alpha) \cap 0^*$ and neither $u0$ nor $u1$ is in $\text{pos}(\alpha)$, then α/u is the tail of α .

A *type environment* is a function from a finite subset of \mathcal{X} to \mathcal{T} (understood as a set of ordered pairs). An element of a type environment (x, α) is written as $x : \alpha$, and a type environment is usually written in the form of a list $x_1 : \alpha_1, \dots, x_n : \alpha_n$, with the understanding that x_1, \dots, x_n are pairwise distinct. We use upper-case Greek letters Γ, Δ, \dots for type environments. We also use usual notations for functions, like $\Gamma(x)$ (the type α such that $x : \alpha \in \Gamma$), $\text{dom}(\Gamma)$ (the domain of Γ), $\text{ran}(\Gamma)$ (the range), and $\Gamma \upharpoonright X$ (Γ restricted to a set X of variables). An expression of the form $\Gamma \Rightarrow \alpha$, consisting of a type environment, the symbol \Rightarrow , and a type, is called a *sequent*. A *typing judgment* is an expression of the form $\Gamma \Rightarrow M : \alpha$, which is like a sequent except that it contains in addition a λ -term M (and a colon following it).

The following axiom schema and the *introduction* ($\rightarrow I$) and *elimination* ($\rightarrow E$) rules determine what typing judgments are *derivable*:

$$x : \alpha \Rightarrow x : \alpha$$

$$\frac{\Gamma \Rightarrow M : \beta}{\Gamma - \{x : \alpha\} \Rightarrow \lambda x.M : \alpha \rightarrow \beta} \rightarrow I \quad (\text{proviso: } \Gamma \cup \{x : \alpha\} \text{ is a type environment})$$

$$\frac{\Gamma \Rightarrow M : \alpha \rightarrow \beta \quad \Delta \Rightarrow N : \alpha}{\Gamma \cup \Delta \Rightarrow MN : \beta} \rightarrow E \quad (\text{proviso: } \Gamma \cup \Delta \text{ is a type environment})$$

The proviso in $\rightarrow I$ means that either $x : \alpha \in \Gamma$ or $x \notin \text{dom}(\Gamma)$. In an instance of the elimination rule, the left premise is called the *major premise*, and the right premise is called the *minor premise*.

The rules of introduction and elimination are understood in the usual way to sanction inference steps. A *deduction* of $\Gamma \Rightarrow M : \alpha$ is a tree whose nodes are labeled by typing judgments such that (i) the root node is labeled by $\Gamma \Rightarrow M : \alpha$, (ii) each leaf node is labeled by an axiom, and (iii) each non-leaf node is sanctioned by the introduction rule (in case it has one child) or the elimination rule (in case it has two children). A deduction of $\Gamma \Rightarrow M : \alpha$ is called a deduction for M . If there is a deduction of $\Gamma \Rightarrow M : \alpha$, we write $\vdash \Gamma \Rightarrow M : \alpha$ and say that $\Gamma \Rightarrow M : \alpha$ is *derivable*. A sequent $\Gamma \Rightarrow \alpha$ is *inhabited* if there is a λ -term M such that $\Gamma \Rightarrow M : \alpha$ is derivable, in which case M is called an *inhabitant* of $\Gamma \Rightarrow \alpha$ and $\Gamma \Rightarrow \alpha$ is called a *typing* of M . A λ -term M is *typable* if it has a typing. Note that if $\Gamma \Rightarrow \alpha$ is a typing of M , then $\text{dom}(\Gamma) = \text{FV}(M)$.⁴

Clearly, the structure of a deduction \mathcal{D} for M exactly reflects the structure of M , and we can use positions in $\text{pos}(M)$ to refer to occurrences of judgments in \mathcal{D} .

A typing $\Gamma \Rightarrow \alpha$ of a λ -term M is *principal* if for every typing $\Delta \Rightarrow \beta$ of M , there is a type substitution σ such that $\beta = \alpha\sigma$ and for every variable $x \in \text{FV}(M)$, $\Delta(x) = \Gamma(x)\sigma$. Similarly, a *principal deduction* for M is a deduction for M from which all other deductions for M can be obtained by type substitution. It is known that every typable λ -term has a principal typing and principal deduction.

Figure 1 shows an example of a deduction, with the name of the rule written next to each inference step. This deduction is a principal deduction for $(\lambda x.yxx)(wz)$.

Note that the type environment Δ in each typing judgment $\Delta \Rightarrow N : \beta$ appearing in a deduction is recoverable from the remaining part of the

⁴This property will not hold if we use an alternative formulation of the axiom which is common in the literature: $\Gamma, x : \alpha \Rightarrow x : \alpha$. It is more convenient for our purposes to adopt a definition that implies this property.

$$\frac{\frac{\frac{y : p_2 \rightarrow p_2 \rightarrow p_1 \Rightarrow y : p_2 \rightarrow p_2 \rightarrow p_1 \quad x : p_2 \Rightarrow x : p_2}{y : p_2 \rightarrow p_2 \rightarrow p_1, x : p_2 \Rightarrow yx : p_2 \rightarrow p_1} \rightarrow E \quad x : p_2 \Rightarrow x : p_2}{y : p_2 \rightarrow p_2 \rightarrow p_1 \Rightarrow \lambda x.yxx : p_2 \rightarrow p_1} \rightarrow I \quad \frac{z : p_3 \rightarrow p_2 \Rightarrow z : p_3 \rightarrow p_2 \quad w : p_3 \Rightarrow w : p_3}{z : p_3 \rightarrow p_2, w : p_3 \Rightarrow zw : p_2} \rightarrow E}{y : p_2 \rightarrow p_2 \rightarrow p_1, z : p_3 \rightarrow p_2, w : p_3 \Rightarrow (\lambda x.yxx)(zw) : p_1} \rightarrow E$$

Figure 1. An example of a deduction.

$$\frac{\frac{\frac{y : p_2 \rightarrow p_2 \rightarrow p_1 \quad x : p_2}{yx : p_2 \rightarrow p_1} \rightarrow E \quad x : p_2}{\lambda x.yxx : p_2 \rightarrow p_1} \rightarrow I \quad \frac{z : p_3 \rightarrow p_2 \quad w : p_3}{zw : p_2} \rightarrow E}{(\lambda x.yxx)(zw) : p_1} \rightarrow E$$

Figure 2. A deduction in abbreviated form.

deduction. For this reason, we sometimes use an abbreviated notation for a deduction where the type environment and the symbol \Rightarrow are dropped. Figure 2 shows the deduction in Figure 1 under this convention.

The relation of β -reduction naturally extends to deductions. If \mathcal{D} is a deduction of $\Gamma \Rightarrow M : \alpha$ and $M \rightarrow_\beta M'$, then there is a deduction \mathcal{D}' of $\Gamma \upharpoonright \text{FV}(M') \Rightarrow M' : \alpha$ induced by the given one-step β -reduction from M to M' . This is written $\mathcal{D} \rightarrow_\beta \mathcal{D}'$. Similarly, we write $\mathcal{D} \rightarrow_\beta \mathcal{D}'$ and say that \mathcal{D} β -reduces to \mathcal{D}' when either the associated λ -terms are α -equivalent and \mathcal{D} and \mathcal{D}' are otherwise identical or \mathcal{D} and \mathcal{D}' are related by the transitive closure of \rightarrow_β . We say that a deduction of $\Gamma \Rightarrow M : \alpha$ is *in β -normal form* when M is β -normal. It is known that every deduction β -reduces to one in β -normal form.

Similarly, if \mathcal{D} is a deduction of $\Gamma \Rightarrow M : \alpha$ and $M \rightarrow_\eta M'$, then there is an induced deduction \mathcal{D}' of $\Gamma \Rightarrow M' : \alpha$, in which case we say that \mathcal{D}' η -reduces to \mathcal{D} and write $\mathcal{D} \rightarrow_\eta \mathcal{D}'$.

A deduction is said to be *in η -long form* if every occurrence of a judgment of the form $\Delta \Rightarrow N : \beta \rightarrow \gamma$ in it is either the conclusion of an instance of the introduction rule or the major premise of an instance of the elimination rule. The deduction in Figure 1 is in η -long form. Every deduction can be η -expanded to a deduction of the same judgment in η -long form.

A λ -term M is *η -long relative to $\Gamma \Rightarrow \alpha$* if there is a deduction of $\Gamma \Rightarrow M : \alpha$ that is η -long. Similarly, a λ -term M is *in η -long β -normal form* (or *long normal form* for short) relative to $\Gamma \Rightarrow \alpha$ if it is β -normal and η -long relative to $\Gamma \Rightarrow \alpha$. We simply say that M is *in η -long β -normal form* (or *long normal form*) if M is in η -long β -normal form relative to some typing (or, equivalently, relative to its principal typing). Note that if a λ -term M has a typing $\Gamma \Rightarrow \alpha$, then there is always a λ -term $M' =_{\beta\eta} M$ that is in η -long β -normal form relative to $\Gamma' \Rightarrow \alpha$ for some $\Gamma' \subseteq \Gamma$.

3. Negatively Non-duplicated Sequents

In this section, we state some lemmas that will be important in the proof of our theorem in the next section. Proofs are omitted due to lack of space.

Let $\Gamma \Rightarrow \alpha_0$ be a sequent, where $\Gamma = x_1 : \alpha_1, \dots, x_n : \alpha_n$. The set of *positions* of $\Gamma \Rightarrow \alpha_0$, written $\text{pos}(\Gamma \Rightarrow \alpha_0)$, is defined by $\text{pos}(\Gamma \Rightarrow \alpha_0) = \bigcup_{i=0}^n \{(i, u) \mid u \in \text{pos}(\alpha_i)\}$. An occurrence of a type γ at position $(i, u) \in \text{pos}(\Gamma \Rightarrow \alpha_0)$ is *positive* if $i = 0$ and u is positive, or $1 \leq i \leq n$ and u is negative; otherwise, the occurrence is *negative*.

We let $\text{Possub}(\Gamma \Rightarrow \alpha_0) = \text{Possub}(\alpha_0) \cup \bigcup_{i=1}^n \text{Negsub}(\alpha_i)$ and $\text{Negsub}(\Gamma \Rightarrow \alpha_0) = \text{Negsub}(\alpha_0) \cup \bigcup_{i=1}^n (\{\alpha_i\} \cup \text{Possub}(\alpha_i))$. The elements of the former (resp. the latter) are positive (resp. negative) subpremises of $\Gamma \Rightarrow \alpha_0$.

LEMMA 3.1. Suppose that an axiom $x : \beta \Rightarrow x : \beta$ occurs in a deduction \mathcal{D} of $\Gamma \Rightarrow M : \alpha$ in β -normal form. Then β is a negative subpremise of $\Gamma \Rightarrow \alpha$.

A deduction (in abbreviated notation) in η -long β -normal form for a λ -term M can be uniquely written in the following way:⁵

$$\frac{\frac{y : \beta_1 \rightarrow \dots \rightarrow \beta_n \rightarrow p \quad \frac{\mathcal{D}_1}{M_1 : \beta_1} \quad \dots \quad \frac{\mathcal{D}_n}{M_n : \beta_n}}{yM_1 \dots M_n : p} \rightarrow E}{\lambda x_1 \dots x_l. yM_1 \dots M_n : \alpha_1 \rightarrow \dots \rightarrow \alpha_l \rightarrow p} \rightarrow I$$

where $y \in \text{FV}(M) \cup \{x_1, \dots, x_l\}$ and each subdeduction \mathcal{D}_i for M_i is in η -long β -normal form.

A sequent $\Gamma \Rightarrow \alpha$ is said to be *negatively non-duplicated* if no atomic type has more than one negative occurrence in it [1]. We say that $\Gamma \Rightarrow \alpha$ has the *negative subpremise property* if for all $\beta, \gamma \in \text{Negsub}(\Gamma \Rightarrow \alpha)$, $\text{tail}(\beta) = \text{tail}(\gamma)$ implies $\beta = \gamma$. The following is obvious from the definition of a subpremise.

LEMMA 3.2. If $\Gamma \Rightarrow \alpha$ is a negatively non-duplicated sequent, then it has the negative subpremise property.

LEMMA 3.3. Let $\Gamma \Rightarrow \alpha$ be a sequent with the negative subpremise property, and suppose that \mathcal{D} is a deduction of $\Gamma \Rightarrow M : \alpha$ in β -normal form. Then for every judgement of the form $\Delta \Rightarrow N : q$ that occurs in \mathcal{D} , $\Delta \Rightarrow q$ has the negative subpremise property.

⁵As usual, a double horizontal line abbreviates a sequence of inference steps sanctioned by the same inference rule.

LEMMA 3.4. Let $\Gamma \Rightarrow p$ be a sequent with the negative subpremise property. Suppose that \mathcal{D} is a deduction of $\Gamma \Rightarrow M : p$ in η -long β -normal form. If a typing judgement $\Gamma' \Rightarrow M' : p$ occurs in \mathcal{D} , then $M = M'$.

LEMMA 3.5. Let $\Gamma \Rightarrow \alpha$ be a negatively non-duplicated sequent, and let \mathcal{D} be a deduction of $\Gamma \Rightarrow M : \alpha$ in η -long β -normal form. For every occurrence of a judgment $\Delta \Rightarrow N : \beta$ in \mathcal{D} that is not a major premise of $\rightarrow E$, the sequent $\Delta \Rightarrow \beta$ is negatively non-duplicated.

We call a type environment $\Gamma = \{x_1 : \alpha_1, \dots, x_n : \alpha_n\}$ *injective* if $\alpha_i = \alpha_j$ implies $i = j$.

LEMMA 3.6. Suppose that $\Gamma \Rightarrow \alpha$ and $\Gamma' \Rightarrow \alpha$ are negatively non-duplicated sequents, $\Gamma \cup \Gamma'$ is an injective type environment, and $\Gamma \cup \Gamma' \Rightarrow \alpha$ has the negative subpremise property. If $\vdash \Gamma \Rightarrow M : \alpha$ and $\vdash \Gamma' \Rightarrow M' : \alpha$, then $M =_{\beta\eta} M'$.

Aoto and Ono's [2] theorem is derived as an immediate corollary to Lemma 3.6.

THEOREM 3.7 (Aoto and Ono). Suppose that $\Gamma \Rightarrow M : \alpha$ and $\Delta \Rightarrow N : \alpha$ are derivable and $\Gamma \cup \Delta \Rightarrow \alpha$ is a negatively non-duplicated sequent. Then $M =_{\beta\eta} N$.

4. Negatively Non-duplicated Sequents and Almost Affine λ -terms

A deduction is *almost affine* if every instance of the elimination rule in it

$$\frac{\Gamma \Rightarrow M : \alpha \rightarrow \beta \quad \Delta \Rightarrow N : \alpha}{\Gamma \cup \Delta \Rightarrow MN : \beta} \rightarrow E$$

satisfies the condition $\text{ran}(\Gamma \cap \Delta) \subseteq \text{At}$. A λ -term M is *almost affine relative to* $\Gamma \Rightarrow \alpha$ if there is an almost affine deduction of $\Gamma \Rightarrow M : \alpha$. We simply say that M is *almost affine* if M is almost affine relative to some typing (or, equivalently, relative to its principal typing). Figure 1 is an example of an almost affine deduction. Unlike the class of affine λ -terms, the class of almost affine λ -terms is clearly not closed under β -reduction. For instance, the λ -term $(\lambda x.yxx)(zw)$ in Figure 1 β -reduces to $y(zw)(zw)$, which is not almost affine.

Kanazawa [12, Theorem 3.41] gives a simple proof that a principal typing of an almost affine λ -term is always negatively non-duplicated. In this section, we show that a long normal inhabitant of a negatively non-duplicated sequent always β -expands to some almost affine λ -term.

We say that a β -reduction step from a deduction \mathcal{D} of $\Gamma \Rightarrow M : \alpha$ to a deduction \mathcal{D}' of $\Gamma \upharpoonright \text{FV}(M') \Rightarrow M' : \alpha$ is *atomic duplicating* if in the subdeduction of \mathcal{D} that is associated with the contracted β -redex $(\lambda x.P)Q$ of M

$$\frac{\frac{\frac{\vdots}{\Delta_1 \Rightarrow P : \gamma}}{\Delta_1 - \{x : p\} \Rightarrow \lambda x.P : p \rightarrow \gamma} \rightarrow I \quad \frac{\vdots}{\Delta_2 \Rightarrow Q : p}}{(\Delta_1 - \{x : p\}) \cup \Delta_2 \Rightarrow (\lambda x.P)Q : \gamma} \rightarrow E$$

the type p is atomic and the λ -term P contains more than one free occurrence of x .

We need a few more pieces of terminology for the following proofs. Suppose that a λ -term of the form $xP_1 \dots P_n$ occurs at position u of a λ -term M . Then the occurrence of P_i at position $u0^{n-i}1$ is called an *argument* of the occurrence of x at position $u0^n$. Suppose moreover that P_i has the form $\lambda z_1 \dots z_m. \lambda y.Q$. Then we say that the occurrence of x at $u0^n$ *directly controls* the occurrences of y whose binder is the occurrence of $\lambda y.Q$ at $u0^{n-i}10^m$. We say that an occurrence of a variable x *controls* an occurrence of a variable y if they stand in the transitive closure of the relation of direct control [17]. It is easy to see that if $M = M_1M_2$ is a λ -term in β -normal form, then every bound occurrence of a variable in M is controlled by some free occurrence of a variable in M .

Let M be a typable λ -term, and suppose that an occurrence of x at position u of M controls an occurrence of y at position v . Let \mathcal{D} be a deduction for M , and suppose that $x : \alpha \Rightarrow x : \alpha$ and $y : \beta \Rightarrow y : \beta$ are the occurrences of axioms at positions u and v of \mathcal{D} , respectively. Then it is easy to see that β is a positive subpremise of α .

LEMMA 4.1. If $\Gamma \Rightarrow \alpha$ is a negatively non-duplicated sequent and \mathcal{D} is a deduction of $\Gamma \Rightarrow M : \alpha$ in η -long β -normal form, then there is an almost affine deduction \mathcal{D}' of $\Gamma \Rightarrow M' : \alpha$ such that $\mathcal{D}' \rightarrow_\beta \mathcal{D}$ by atomic duplicating β -reduction steps.

PROOF. The proof is by induction on the complexity of (i.e., the number of occurrences of \rightarrow in) $\Gamma \Rightarrow \alpha$. We assume that M is regular.

Case 1. \mathcal{D} ends in $\rightarrow I$. This case is straightforward and is omitted.

Case 2. \mathcal{D} does not end in $\rightarrow I$. Since \mathcal{D} is in η -long β -normal form, $\alpha = p \in \text{At}$, M is of the form $yM_1 \dots M_n$ ($n \geq 0$), and the deduction \mathcal{D} is of the following form:

$$\frac{\frac{y : \beta_1 \rightarrow \dots \rightarrow \beta_n \rightarrow p \quad \frac{\mathcal{D}_1}{\Gamma_1 \Rightarrow M_1 : \beta_1} \quad \dots \quad \frac{\mathcal{D}_n}{\Gamma_n \Rightarrow M_n : \beta_n}}{y : \beta_1 \rightarrow \dots \rightarrow \beta_n \rightarrow p, \Gamma_1 \cup \dots \cup \Gamma_n \Rightarrow yM_1 \dots M_n : p} \rightarrow E$$

Here, $\Gamma_i = \Gamma \upharpoonright \text{FV}(M_i)$. Note that $y \notin \text{FV}(M_1) \cup \dots \cup \text{FV}(M_n)$ by Lemmas 3.2 and 3.4. Let

$$\widehat{\Gamma} = \{x : \gamma \in \Gamma \mid \gamma \notin \text{At} \text{ and } x : \gamma \in \Gamma_i \cap \Gamma_j \text{ for some } i, j \text{ such that } i \neq j\}.$$

Case 2.1. $\widehat{\Gamma} = \emptyset$. Then for $i = 1, \dots, n$,

$$\text{ran}((\{y : \beta_1 \rightarrow \dots \rightarrow \beta_n \rightarrow p\} \cup \Gamma_1 \cup \dots \cup \Gamma_{i-1}) \cap \Gamma_i) \subseteq \text{At}. \quad (*)$$

Since $\Gamma_i \Rightarrow \beta_i$ is negatively non-duplicated and $\Gamma_i \Rightarrow \beta_i$ is less complex than $\Gamma \Rightarrow p$, we can apply the induction hypothesis to \mathcal{D}_i and obtain an almost affine deduction \mathcal{D}'_i of $\Gamma_i \Rightarrow M_i : \beta_i$ that β -reduces to \mathcal{D}_i by atomic duplicating β -reduction steps. Let \mathcal{D}' be the following deduction:

$$\frac{y : \beta_1 \rightarrow \dots \rightarrow \beta_n \rightarrow p \quad \Gamma_1 \Rightarrow M'_1 : \beta_1 \quad \dots \quad \Gamma_n \Rightarrow M'_n : \beta_n}{y : \beta_1 \rightarrow \dots \rightarrow \beta_n \rightarrow p, \Gamma_1 \cup \dots \cup \Gamma_n \Rightarrow yM'_1 \dots M'_n : p} \xrightarrow{E} \mathcal{D}'$$

By (*), \mathcal{D}' is an almost affine deduction. It is clear that \mathcal{D}' β -reduces to \mathcal{D} by atomic β -reduction steps.

Case 2.2. $\widehat{\Gamma} \neq \emptyset$. In this case we must have $n \geq 1$. Suppose $\widehat{\Gamma} = \{y_1 : \alpha_1, \dots, y_m : \alpha_m\}$ and $q_i = \text{tail}(\alpha_i)$ for $i = 1, \dots, m$.

Our goal is to find a k such that y_k always occurs with the same arguments up to α -equivalence, and there are a λ -term N and a sequence of λ -terms \vec{P} satisfying the following properties:

- $M \equiv_\alpha N[z := y_k \vec{P}]$,
- $x \in \text{FV}(N) \cap \text{FV}(y_k \vec{P})$ implies $\Gamma(x) \in \text{At}$.

If such a k is found, then we can “extract” (α -variants of) the deduction \mathcal{F} of $\Gamma'' \Rightarrow y_k \vec{P} : q_k$ from \mathcal{D} and form a deduction \mathcal{E} of $\Gamma', z : q_k \Rightarrow N : p$ so that the deduction

$$\frac{\frac{\Gamma', z : q_k \Rightarrow N : p}{\Gamma' \Rightarrow \lambda z. N : q_k \rightarrow p} \xrightarrow{E} \mathcal{E} \quad \Gamma'' \Rightarrow y_k \vec{P} : q_k \xrightarrow{\mathcal{F}}}{\Gamma' \cup \Gamma'' \Rightarrow (\lambda z. N)(y_k \vec{P}) : p} \xrightarrow{E}$$

β -reduces to \mathcal{D} by an atomic duplicating β -reduction step.

We begin by showing the following:

CLAIM. For every $i = 1, \dots, m$, there are sets $T_i \subseteq \bigcup_{j \neq i} (\{\alpha_j\} \cup \text{Possub}(\alpha_j))$ and $U_i \subseteq \text{ran}(\Gamma) \cap \text{At}$ such that whenever $\Delta \Rightarrow y_i \vec{P} : q_i$ occurs in \mathcal{D} , we have $\text{ran}(\Delta) = \{\alpha_i\} \cup T_i \cup U_i$.

First, we note that $\text{ran}(\Delta)$ must be constant for every such occurrence. For, suppose that $\Delta' \Rightarrow y_i \vec{P}' : q_i$ also occurs in \mathcal{D} . By Lemma 3.5, $\Delta \Rightarrow q_i$ and $\Delta' \Rightarrow q_i$ are both negatively non-duplicated. By Lemma 3.1, $\text{ran}(\Delta) \cup \text{ran}(\Delta') \subseteq \text{Negsub}(\Gamma \Rightarrow p)$, so $\Delta \cup \Delta' \Rightarrow q_i$ has the negative subpremise property. Define a renaming of variables θ by $\theta(z') = z$ if $\Delta(z) = \Delta'(z')$ for some z , and $\theta(z') = z'$ otherwise. Then $\Delta \Rightarrow y_i \vec{P} : q_i$ and the result of applying θ to $\Delta' \Rightarrow y_i \vec{P}' : q_i$ together satisfy the conditions of Lemma 3.6, and we can conclude $\text{ran}(\Delta) = \text{ran}(\Delta')$.

Now suppose that $\Delta \Rightarrow y_i \vec{P} : q_i$ occurs in \mathcal{D}_j . Then by Lemma 3.1 again,

$$\text{ran}(\Delta) \subseteq \text{Negsub}(\Gamma_j \Rightarrow \beta_j) = \bigcup \{ \{\gamma\} \cup \text{Possub}(\gamma) \mid \gamma \in \text{ran}(\Gamma_j) \} \cup \text{Negsub}(\beta_j). \quad \blacksquare$$

Since $y_i : \alpha_i \in \widehat{\Gamma}$, the same condition must hold with k in place of j for some $k \neq j$. Since $y : \beta_1 \rightarrow \dots \rightarrow \beta_n \rightarrow p \in \Gamma$ and $\Gamma \Rightarrow p$ is negatively non-duplicated, we have $\text{Negsub}(\Gamma_j \Rightarrow \beta_j) \cap \text{Negsub}(\Gamma_k \Rightarrow \beta_k) = \bigcup \{ \{\gamma\} \cup \text{Possub}(\gamma) \mid \gamma \in \text{ran}(\Gamma_j \cap \Gamma_k) \}$. It follows that $\text{ran}(\Delta) \subseteq (\text{ran}(\Gamma) \cap \text{At}) \cup \bigcup \{ \{\gamma\} \cup \text{Possub}(\gamma) \mid \gamma \in \text{ran}(\widehat{\Gamma}) \}$. Since $y_i : \alpha_i \in \Delta$ and $\Delta \Rightarrow q_i$ is negatively non-duplicated, we have $\text{ran}(\Delta - \{y_i : \alpha_i\}) \cap \text{Possub}(\alpha_i) = \emptyset$. This establishes the claim.

We define two relations \prec_1 and \prec_2 on $\{1, \dots, m\}$:

$$i \prec_1 j \text{ iff } T_i \cap \text{Possub}(\alpha_j) \neq \emptyset, \quad i \prec_2 j \text{ iff } \alpha_i \in T_j.$$

The relation $i \prec_1 j$ means that y_i always occurs with an argument that contains a variable controlled by an outside occurrence of y_j . (Notice that the fact that $\Gamma \Rightarrow p$ is negatively non-duplicated means that any occurrence of a variable of type $\delta \in \text{Possub}(\alpha_j)$ must be controlled by an occurrence of y_j .) The relation $i \prec_2 j$ holds if and only if y_j always occurs with an argument that contains an occurrence of y_i .

Since $\{\alpha_1, \dots, \alpha_m\} \subseteq \text{ran}(\Gamma)$ and $\Gamma \Rightarrow p$ is negatively non-duplicated, $(\{\alpha_i\} \cup \text{Possub}(\alpha_i)) \cap (\{\alpha_j\} \cup \text{Possub}(\alpha_j)) = \emptyset$ if $i \neq j$. Since $T_i \subseteq \bigcup_{j \neq i} (\{\alpha_j\} \cup \text{Possub}(\alpha_j))$, it follows that both \prec_1 and \prec_2 are irreflexive. By the above characterization of \prec_1 and \prec_2 , it is easy to see that \prec_2 is transitive and $i \prec_1 j$ implies $i \prec_2 j$. Therefore, the transitive closure \prec_1^+ of \prec_1 is included in \prec_2 and is thus also irreflexive. This means that both \prec_1^+ and \prec_2 are strict partial orders. Note that $i \prec_1^+ j$ implies that every occurrence of y_i occurs inside an argument of an occurrence of y_j , while $i \prec_2 j$ is consistent with the possibility that some occurrence of y_i does not occur inside an argument of any occurrence of y_j . So in general, \prec_1^+ can be a proper subrelation of \prec_2 .

We now show

- (†) If $i \prec_1 j$ and $i \prec_2 h$, then $j \prec_2 h$ or $j = h$ or $h \prec_1 j$.
- (‡) If $i \prec_1^+ j$ and $i \prec_2 h$, then $j \prec_2 h$ or $j = h$ or $h \prec_1^+ j$.

To show (†), suppose $i \prec_1 j$ and $i \prec_2 h$. Since $i \prec_2 h$, we have $\alpha_i \in T_h$ and a judgment of the form $\Delta \Rightarrow y_i \vec{P} : q_i$ with $\text{ran}(\Delta) = \{\alpha_i\} \cup T_i \cup U_i$ must occur in a deduction of a judgment of the form $\Theta \Rightarrow y_h \vec{Q} : q_h$ with $\text{ran}(\Theta) = \{\alpha_h\} \cup T_h \cup U_h$. Since $i \prec_1 j$, there is a type $\delta \in T_i \cap \text{Possub}(\alpha_j)$. By Lemma 3.1, δ must be a negative subpremise of $\Theta \Rightarrow q_h$, so $\delta \in \{\alpha_h\} \cup \text{Possub}(\alpha_h) \cup \bigcup \{\{\gamma\} \cup \text{Possub}(\gamma) \mid \gamma \in T_h\} \cup U_h$. Since $\{\alpha_h, \alpha_j\} \cup U_h \subseteq \text{ran}(\Gamma)$ and $\Gamma \Rightarrow p$ is negatively non-duplicated, $\delta \neq \alpha_h$ and $\delta \notin U_h$, which leaves two cases: (i) $\delta \in \text{Possub}(\alpha_h)$, or (ii) $\delta \in \{\gamma\} \cup \text{Possub}(\gamma)$ for some $\gamma \in T_h$. If (i) holds, $\text{Possub}(\alpha_j) \cap \text{Possub}(\alpha_h) \neq \emptyset$ and it follows that $j = h$. If (ii) holds, either $\alpha_j \in T_h$ and hence $j \prec_2 h$, or $T_h \cap \text{Possub}(\alpha_j) \neq \emptyset$ and hence $h \prec_1 j$.

The property (‡) can be proved by induction on $n \geq 1$ such that $i \prec_1^n j$. The property (†) takes care of the induction basis ($n = 1$). For the induction step, suppose $i \prec_1^n j' \prec_1 j$ and $i \prec_2 h$. By induction hypothesis, $j' \prec_2 h$ or $j' = h$ or $h \prec_1^+ j'$. In case $j' = h$ or $h \prec_1^+ j'$, since $j' \prec_1 j$, we have $h \prec_1^+ j$. In case $j' \prec_2 h$, (†) gives $j \prec_2 h$ or $j = h$ or $h \prec_1 j$.

Now let k be a \prec_2 -minimal element among the \prec_1^+ -maximal elements of $\{1, \dots, m\}$. Using (‡), we can show that $i \prec_2 k$ implies $i \prec_1^+ k$. To see this, suppose $i \prec_2 k$. Since k is \prec_2 -minimal among the \prec_1^+ -maximal elements, i is not \prec_1^+ -maximal. Let j be a \prec_1^+ -maximal element such that $i \prec_1^+ j$. Then since $j \not\prec_2 k$ and $k \not\prec_1^+ j$, we can conclude by (‡) that $j = k$ and hence $i \prec_1^+ k$. This means that if some occurrence of y_i is in an argument of an occurrence of y_k , every occurrence of y_i is in an argument of an occurrence of y_k . Since the \prec_1^+ -maximality of k means $T_k \subseteq \text{ran}(\widehat{\Gamma})$, we have $\{\alpha_k\} \cup T_k \cup U_k \subseteq \text{ran}(\Gamma)$. Let $\Gamma'' = \{x : \Gamma(x) \mid \Gamma(x) \in \{\alpha_k\} \cup T_k \cup U_k\}$. Then whenever $\Delta \Rightarrow y_k \vec{P} : q_k$ occurs in \mathcal{D} for some \vec{P} , we must have $\Delta = \Gamma''$. Since \mathcal{D} is in η -long β -normal form, Theorem 3.7 implies that \vec{P} is also unique up to α -equivalence. Let \mathcal{F} be a subdeduction of \mathcal{D} that ends in $\Gamma'' \Rightarrow y_k \vec{P} : q_k$. Clearly, \mathcal{F} is in η -long β -normal form. By the above remark, if $y_i : \alpha_i \in \Gamma''$, every occurrence of y_i in M is inside an occurrence of (an α -variant of) $y_k \vec{P}$.

Pick a fresh variable z . Let N be the result of replacing every occurrence of (an α -variant of) $y_k \vec{P}$ in M by z , and let \mathcal{E} be the result of similarly replacing every occurrence of (an α -variant of) \mathcal{F} in \mathcal{D} by a single-line deduction $z : q_k \Rightarrow z : q_k$. Then \mathcal{E} must be a deduction of a judgment $\Gamma', z : q_k \Rightarrow N : p$ in η -long β -normal form for some type environment Γ' that satisfies $\Gamma' \cup \Gamma'' = \Gamma$ and $\Gamma' \cap \Gamma'' \subseteq U_k \subseteq At$.

Let \tilde{D} be the following deduction:

$$\frac{\frac{\Gamma', z : q_k \Rightarrow N : p}{\Gamma' \Rightarrow \lambda z.N : q_k \rightarrow p} \xrightarrow{I} \xrightarrow{\mathcal{E}} \quad \Gamma'' \Rightarrow y_k \vec{P} : q_k \xrightarrow{\mathcal{F}}}{\Gamma \Rightarrow (\lambda z.N)(y_k \vec{P}) : p} \rightarrow E$$

Clearly, $\tilde{\mathcal{D}}$ β -reduces to \mathcal{D} by an atomic duplicating β -reduction step.

Since $\Gamma', z : q_k \Rightarrow p$ and $\Gamma'' \Rightarrow q_k$ are both less complex than $\Gamma \Rightarrow p$, we can apply the induction hypothesis to \mathcal{E} and \mathcal{F} , obtaining almost affine deductions \mathcal{E}' and \mathcal{F}' of $\Gamma', z : q_k \Rightarrow N' : p$ and of $\Gamma'' \Rightarrow Q : q_k$, which β -reduce to \mathcal{E} and \mathcal{F} by atomic duplicating β -reduction steps, respectively. Let $\tilde{\mathcal{D}}'$ be the following deduction:

$$\frac{\frac{\Gamma', z : q_k \Rightarrow N' : p}{\Gamma' \Rightarrow \lambda z.N' : q_k \rightarrow p} \xrightarrow{I} \xrightarrow{\mathcal{E}'} \quad \Gamma'' \Rightarrow Q : q_k \xrightarrow{\mathcal{F}'}}{\Gamma \Rightarrow (\lambda z.N')Q : p} \rightarrow E$$

Then $\tilde{\mathcal{D}}'$ is an almost affine deduction that β -reduces to \mathcal{D} by atomic duplicating β -reduction steps.

We have exhausted all cases and the inductive proof is complete. \blacksquare

THEOREM 4.2. Every inhabitant of a negatively non-duplicated sequent is $\beta\eta$ -equal to an almost affine λ -term.

COROLLARY 4.3. Let M be a λ -term in η -long β -normal form. Then M β -expands to an almost affine λ -term if and only if M has a negatively non-duplicated principal typing.

REMARK. We cannot weaken “long normal form” in the statement of Lemma 4.1 to “ β -normal form”. If a λ -term M is β -normal but not η -long relative to a negatively non-duplicated typing, there may be no almost affine λ -term that β -reduces to M . For example, $M = w(xy)(x(\lambda z.yz))$ has a negatively non-duplicated typing, but M does not β -expand to any almost affine λ -term. Note that M is $\beta\eta$ -equal to an almost affine λ -term $(\lambda v.wvv)(x(\lambda z.yz))$.

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