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DEGREES, REDUCTIONS AND REPRESENTABILITY

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DEGREES, REDUCTIONS AND REPRESENTABILITY IN THE LAMBDA CALCULUS.

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The three chapters of this preprint can be read independently. Only some technical lemma's used in I are proved in II.
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INTRODUCTION.

A \( \lambda \)-theory \( T \) is a consistent set of equations between \( \lambda \)-terms closed under derivability. The degree of \( T \) is the degree of the set of Gödel numbers of its elements. A \( \lambda \)-theory \( T \) is sensible iff \( T \vdash K_0 = \{ M = N \mid M, N \text{ unsolvable} \} \).

In §1 it is proved that the theory \( K \) is \( \Sigma^0_1 \)-complete. We present Wadsworth's proof that its unique maximal consistent extension \( K^* (= \text{Th}(D_\infty)) \) is \( \Pi^0_1 \)-complete.

In §2 it is proved that \( K_0 ^* (= \lambda \eta \text{-calculus } + K) \) is not closed under the \( \omega \)-rule (see [1]).

In §3 arguments are given to conjecture that \( K_\omega (= \lambda + K + \omega \text{-rule}) \) is \( \Pi^1_1 \)-complete.

This is done by representing recursive sets of sequence numbers as \( \lambda \)-terms and by connecting well-foundedness of trees with provability in \( K_\omega \).

In §4 a set of equations independent over \( K_0 \) will be constructed. From this it follows that there are \( 2^{\aleph_0} \) sensible theories \( T \) s.t. \( K \subset T \subset K^* \) and \( 2^{\aleph_0} \) sensible hard models of arbitrarily high degrees.

In §5 some non-provability results needed in §1, 2 are established. For this purpose one uses the theory \( K_0 \) extended with a reduction relation for which the Church-Rosser theorem holds. The concept of Gross reduction is used in order to show that certain terms have no common reduct.

Familiarity with [2] is assumed.
§1. Degrees of \( K, K^* \) and \( K_\omega \).

The \( \lambda \)-theory \( K \) has a unique maximal consistent extension \( K^* \) ([2] §4). Let \( K_\omega \) be the set of equations provable in \( \lambda + K + \omega \)-rule. Then one has
\[
K \subseteq K_\eta \subseteq K_\omega \subseteq K^* .
\]
The first two inclusions are trivial, the last one follows from the fact that \( K^* = \text{Th}(D_\omega) \) and \( D_\omega \) satisfies the \( \omega \)-rule, see [6]. Moreover the inclusions are proper. \( K \neq K_\eta \) follows from the C-R property for \( K_\eta \).

\( K_\eta \neq K_\omega \) is proved in 1.9. \( K_\omega \neq K^* \) follows by an extension of the consistency proof in [1]: It can be proved that if \( K_\omega \vdash M=I \), then \( \lambda \vdash M^I = I \) where \( \vec{I} \) is some sequence of I's. If \( K_\omega = K^* \), then \( K_\omega \vdash J=I \), where \( J \) is Wadsworth's term
\[
Y(\lambda jxy.x(jy)) ,
\]
since \( J \) and \( I \) have equivalent Böhm trees [2], 6.7. So \( \lambda \vdash J^\vec{I}=I \), contradicting the C-R property for the \( \lambda \)-calculus.

It will be proved that \( K(\eta) \) is \( \Sigma_2^0 \)-complete and that \( K^* \) is \( \Pi_2^0 \)-complete. It is conjectured that \( K_\omega \) is \( \Pi_1^1 \)-complete.

Notation. \( \Omega \) denotes the term \((\lambda x. xx)(\lambda x. xx)\).

If \( \rightarrow \) is a reduction relation, \( \ast \rightarrow \) denotes its transitive reflexive closure.

\[
\begin{align*}
\beta \rightarrow & \quad, \gamma \rightarrow \\
\beta \gamma \rightarrow & = \beta \rightarrow \cup \gamma \rightarrow 
\end{align*}
\]

1.1 Lemma. Let \( R(x) \) be an r.e. predicate (on \( \omega \)). Then for some term \( F \)
\[
\begin{align*}
K & \vdash F_n = I \text{ if } R(n) \\
K & \vdash F_n = \Omega \text{ if } \neg R(n).
\end{align*}
\]

Proof.

Let \( R(x) \iff \exists y A(x,y) \) with \( A \) recursive. Define by the fixed point combinator
\[
F_x = \begin{cases} I & \text{if } A(x,y) \text{ then } I \\ F(x+1) & \text{else} \end{cases}
\]
Then \( F \) works, since if \( \neg R(n) \), then \( F_n \) is unsolvable, hence \( \Omega \) in \( K \).

1.2 Def. (i) Ordered tuples are represented as terms as follows:
\[
\begin{align*}
\langle M_0 \rangle & = M_0 \\
\langle M_0, \ldots, M_{n+1} \rangle & = [M_0, \langle M_1, \ldots, M_{n+1} \rangle]
\end{align*}
\]
where \([ , \,] \) is some pairing with inverses \( \lambda x.(x)_0, \lambda x.(x)_1 \).

(ii) If \( M_i \) is a definable sequence of terms (i.e. for some \( M, \vdash M_i = M_i \) for all \( i \)), then the infinite sequence \( \langle M_i \rangle \) is represented as a term \( A_\Omega \), where \( A \) is such that \( A_\vec{n} \vdash [M_n, A_{n+1}] \). \( A \) exists by the fixed point theorem.
1.3 Lemma. There is a term $\lambda x. \pi_i x$ such that $\lambda \vdash \pi_i (M_j) = M_n$ (for definable sequences $(M_j)$).

Proof.
Define
$$\pi_i x = \text{If } i=0 \text{ then } (x)_0 \text{ else } \pi_{i-1}(x)_1.$$ 

1.4 Lemma. If $(M_i), (N_i)$ are definable sequences then
$$\forall i \in \mathbb{N} \quad K^* \vdash M_i = N_i \iff K^* \vdash (M_i)_{i \in \omega} = (N_i)_{i \in \omega}.$$ 

Proof.

$\Rightarrow$: The Böhm tree of $(M_i)$ is
$$\lambda z.z$$
and similarly for $(N_i)$. By the theorem of Hyland and Wadsworth
$$K^* \vdash P = Q \iff \text{BT}(P) \sim_{\Pi} \text{BT}(Q),$$
see [2] §1.1, it follows that the mentioned trees are equivalent and the result follows.

$\Leftarrow$: By applying $\pi_i$ of 1.3.

1.5 Theorem (Wadsworth [7]). $K^*$ is $\Pi_2^0$-complete.

Proof.

(i) $K^* \vdash M = N \iff M = N \in K^* \iff \forall C \in \mathbb{K} [C(M) \text{ is solvable} \iff C(N) \text{ is solvable}]$
(see [2], §5). The latter is clearly $\Pi_2^0$.

(ii) Let $\forall a \exists b \ A(a, b)$ be any $\Pi_2^0$ predicate; $A$ is recursive (and has a not explicitly mentioned parameter $c$).

By 1.1 there is a term $F$ such that
$$K \vdash F_a = I \text{ if } \exists b \ A(a, b)$$
$$K \vdash F_a = \Omega \text{ else.}$$
Let $H = (F_0, F_1, \ldots), \ H' = (I, I, \ldots)$.
Now
$$\forall a \exists b \ A(a, b) \iff \forall a \ K \vdash F_a = I$$
$$\iff \forall a \ K^* \vdash F_a = I \quad \text{ since } K \subseteq K^* \text{ and } K^* \not\vdash I = \Omega$$
$$\iff K^* \vdash H = H' \quad \text{ by 1.4.}$$
Therefore each $\Pi_2^0$ predicate can be reduced to provability in $K^*$ (since the $H, H'$ can be found uniformly in the parameter $c$ in $A$).
1.6 Theorem. $\mathcal{K}(\eta)$ is $\Sigma_2^0$-complete.

Proof.

(i) The set of axioms $\mathcal{K} = \{ M=N \mid M,N \text{ unsolvable} \}$ is clearly $\Pi_1^0$, therefore they generate a $\Sigma_2^0$ theory.

(ii) Let $\exists a \forall b A(a,b)$ be any $\Sigma_2^0$ predicate. By 1.1 there is a term $F$ such that $\mathcal{K} \vdash FA = \Omega$ if $\forall b A(a,b)$

$= I$ else.

Let $H_i a [I, Fa(H_{i+1})]$ by the fixed point operator.

Let $x,y$ be different variables.

Claim: $\exists a \forall b A(a,b) \iff \mathcal{K}(\eta) \vdash H_x = H_y$.

$\Rightarrow$: If $\exists a \forall b A(a,b)$, then $\mathcal{K} \vdash H_x = [I, I, \ldots, \Omega] = H_y$.

$\Leftarrow$: If $\neg \exists a \forall b A(a,b)$, then $\forall a \mathcal{K} \vdash FA = I$, so $H_i [I, H_{i+1}]$ and $H_0 [I, I, \ldots, H_I]$. Then $\mathcal{K}(\eta) \not\vdash H_x = H_y$ as is proved in §5.

So each $\Sigma_2^0$ predicate can be reduced to provability in $\mathcal{K}(\eta)$. \qed
§2. $\mathcal{K}\eta \not\models \omega$.

2.1 Def. A $\lambda$-theory $T$ is closed under the $\omega$-rule, notation $T \vdash \omega$, if for all closed $F,F'$

\[ T \vdash FZ = F'Z \quad \text{for all closed } Z \Rightarrow \]

\[ T \vdash F = F'. \]

Note that $\text{Th}(\mathcal{M}) \vdash \omega$ iff $\mathcal{M}^0$ is extensional.

In [4] it is shown that $\lambda\eta \not\models \omega$.

Now two proofs will be given that $\mathcal{K}\eta \not\models \omega$.

In the first proof the terms constructed play a symmetric role. Not so in the alternative one. There a term $A$ is constructed which in $\mathcal{K}\eta$ is constant on all closed terms, but not constant in general.

Also in [4] a pseudo-constant term is used to prove $\lambda\eta \not\models \omega$. The construction is totally different however. See also [1].

2.2 Lemma. Let $F^\omega_n = \underbrace{F \ldots F}_n$. Then

\[ \forall Z \text{ closed } \exists n \quad \mathcal{K} \vdash Z^\omega_n = \Omega. \]

Proof.

If $Z$ is unsolvable, then $\mathcal{K} \vdash Z = \Omega$.

Otherwise $Z$ has a head normal form ([2], 4.3) $\lambda x_1 \ldots x_n . y_1 \ldots y_m$. Then $\mathcal{K} \vdash Z^\omega_n = \Omega$. \(\Box\)

2.3 Theorem. $\mathcal{K}\eta \not\models \omega$.

First Proof.

Define a term $O$ such that

\[ O \downarrow \models \lambda y \cdot yZ^\omega_n \quad (O \downarrow n+1 \downarrow y) \]

$O$ can be constructed by the fixed point theorem and an $F$ such that $\lambda \downarrow Fy^n = yZ^\omega_n$. Take e.g. $Fy^n = \text{If Zero } n \text{ then } y \text{ else } Fy(n-1)\Omega$.

Claim 1. $\forall Z \text{ closed } \mathcal{K} \vdash Ox_\varnothing Z = Oy_\varnothing Z$

2. $\mathcal{K}\eta \not\models Ox_\varnothing = Oy_\varnothing$.

As to 1. $\mathcal{K} \vdash Ox_\varnothing Z = Z\Omega(\ldots(Z\Omega(\ldots(Z\Omega^\omega_n(Ox_{n+1}Z))\ldots)) = \ldots$

Hence by 2.1 there exists an $n$ such that

$\mathcal{K} \vdash Ox_\varnothing Z = Z\Omega(\ldots(Z\Omega^{n-1}(\ldots)) = Oy_\varnothing Z$.

As to 2. This is proved in §5.

By the claim $\mathcal{K}\eta \not\models \omega$. \(\Box\)

Alternative proof. Define a term $A$ such that

\[ Ax^n \models \lambda y . y(\Omega(A\Omega)). \]

Then
$\mathcal{K} \vdash AI = \lambda y. y(A\Omega) = \lambda y.(\lambda y. y(A\Omega)) = \ldots = c^n_*(A\Omega) = \ldots$, where $c_*a = \lambda y. ya$.

Claim: $\forall Z$ closed $\mathcal{K} \vdash AZ = AI$. Indeed,

\[
AZ \overset{*}{=} \lambda y. y(A(Z\Omega^n)) = \overset{*}{c^n_*(A(Z\Omega^n))} = \overset{*}{c^n_*(A\Omega)} \overset{*}{AII}
\]

for $n$ large enough by 2.2.

Hence $\forall$ closed $Z \mathcal{K} \vdash AZ = \mathcal{K}(AI)Z$.

But $\mathcal{K}\eta \not\vdash A = \mathcal{K}(AI)$ as is proved in §5. $\Box$

§3. Conjecture: $\mathcal{K}\omega$ is $\Pi_1^1$-complete.

We will give a strong argument to conjecture that $\mathcal{K}\omega$, the $\lambda$-calculus extended by the axioms $\mathcal{K}$ and the $\omega$-rule, is $\Pi_1^1$-complete.

Given a recursive set $T$ of sequence numbers two terms $B_0, B_1$ can be defined.

It will be proved that: $T$ is well-founded $\Rightarrow \mathcal{K}\omega \vdash B_0 = B_1$. The converse is probably true.

3.1 Def. Let $\forall \alpha \exists n R(\alpha(n))$, with $R$ recursive, be any $\Pi_1^1$-predicate.

Define by 1.1 a term $\Box$ such that $\lambda \exists \Box = I$ if $\neg R(s)$

$= \Omega$ if $R(s)$.

As in the proof of 1.5 we do not exhibit explicitly the main parameter $c$; the whole construction is uniform in $c$.

Define by the double fixed point theorem, [1] 3.1, terms $B, A$ such that

\[
\lambda \vdash B_s^S \overset{*}{=} \lambda y. \Box^S(A_{i, n}^S y)
\]

\[
\lambda \vdash A_{i, n}^S \overset{*}{=} \lambda y. [B_{i, n}^S(y^S), y^S(A_{i, n+1}^S y)]
\]

where $*$ is the representation of the concatenation function of sequence numbers.

Finally set $B_0 = B_1(\cdot), B_1 = B_1(\cdot)$. Note $B_1^S = [[\ldots]]_1^S [\ldots]_1^S \ldots \ldots$.

3.2 Theorem. $\forall \alpha \exists n R(\alpha(n)) \Rightarrow \lambda \mathcal{K}\omega \vdash B_0 = B_1$.

Proof.

(i) $R(s) \Rightarrow \lambda \mathcal{K}\omega \vdash B_s^S = B_0^S \overset{1}{=}$. Indeed $R(s) \Rightarrow [\cdot]^S = \Omega \Rightarrow B_0^S = \Omega = B_1^S \overset{1}{=}$. 

(ii) $\forall n [\lambda \mathcal{K}\omega \vdash B_s^S(n) = B_1^S(n)] \Rightarrow \lambda \mathcal{K}\omega \vdash B_s^S = B_1^S \overset{1}{=}$. 

Indeed the assumption implies as in the proof of 2.2 that $\lambda \mathcal{K}\omega \vdash B_s^S \overset{1}{=}$. 

Hence the conclusion follows by the $\omega$-rule.

Now it follows by bar induction from (i), (ii) and the well-foundedness that $\lambda \mathcal{K}\omega \vdash B_0^S = B_1^S$, i.e. $\lambda \mathcal{K}\omega \vdash B_0 = B_1$. $\Box$
For the converse of 3.2, which establishes the conjecture that \( \mathcal{K} \omega \) is \( \Pi_1 \)-complete, a proof-theoretic analysis of \( \mathcal{K} \omega \) is needed.

§4. \( 2^\omega \) sensible hard models.

Let \( T \) be a \( \lambda \)-theory.

A set \( S \) of equations between \( \lambda \)-terms is independent over \( T \) if for \( M=N \in S \)
\( T+S-\{M=N\} \not\models M=N. \)

A set of terms \( X \) is independent over \( T \) if \( S_X = \{M=N | M,N \in X, M \neq N\} \) is independent over \( T \).

We will construct a countable set of closed terms \( \{B_0,B_1,\ldots\} \) independent over \( \mathcal{K} \eta \). Hence the theories \( T_A = \{B_n = B_0 | n \in A\} \), with \( A \subset \omega - \{0\} \), are all different.

Since an equation is provable in a \( \lambda \)-theory iff it is true in its term model, it follows that the closed term models of \( \mathcal{K} + T_A \) are \( 2^\omega \) sensible hard models.

By taking the open term models of \( \mathcal{K} \eta + T_A \), \( 2^\omega \) sensible extensional models are obtained.

A relation \( \rightarrow \) between terms has the Church-Rosser (CR) property iff

\[ i.e. \quad (M \rightarrow N \land M \rightarrow L) \Rightarrow \exists P (N \rightarrow P \land L \rightarrow P). \]

4.1 Def. Let \( B \) be a term such that

\[ Bx \xrightarrow{\beta} \lambda z.(Bx). \quad \text{To be explicit} \]

\[ \text{take } B = \omega \omega \text{ with } \omega = \lambda bxz.(bbx). \]

It will be proved that \( \{B_0,B_1,\ldots\} \) is an independent set over \( \mathcal{K} \eta \).

In order to do this we introduce a reduction relation satisfying the Church-Rosser theorem, which generates the equality in the theory \( \mathcal{K} \eta A = \mathcal{K} \eta + \{B_n = B_0 | n \in A\} \) for \( A \subset \omega - \{0\} \).

4.2 Def. (i) \( \Omega \)-reduction \( \overrightarrow{\Omega} \) is defined by

1. \( H \overrightarrow{\Omega} \Omega \) for all unsolvables \( H \)
2. \( M \overrightarrow{\Omega} N = MZ \overrightarrow{\Omega} NZ, ZM \overrightarrow{\Omega} ZN, \lambda x.M \overrightarrow{\Omega} \lambda x.N \), for all \( Z \).
3. \( M \overrightarrow{\Omega} M. \)

(ii) \( \beta \eta \overrightarrow{\Omega} = \beta \overrightarrow{\Omega} \eta \overrightarrow{\Omega} \).

Clearly \( \beta \eta \overrightarrow{\Omega} \) generates the equality in \( \mathcal{K} \eta \).

4.3 Lemma. \( \beta \eta \overrightarrow{\Omega} \) has the CR property.

Proof:

See [3] §2.30. \( \Box \)
4.4 Def. (i) \( \text{Red}(Bx) = \{ C(x) | Bx \xrightarrow{\beta} C(x) \} \)

(ii) The reduction relation \( \xrightarrow{\alpha} \) is defined by

1. \( C(n) \xrightarrow{\alpha} C(0) \) for all \( n \in A \) and \( C(x) \in \text{Red}(B) \)
2. \( M \xrightarrow{\alpha} N \Rightarrow MZ \xrightarrow{\alpha} NZ, ZM \xrightarrow{\alpha} ZN, \lambda x.M \xrightarrow{\alpha} \lambda x.N \) (all \( Z \))
3. \( M \xrightarrow{\alpha} M. \)

(iii) \( \xrightarrow{\beta \eta \alpha} = \xrightarrow{\beta \eta} \cup \xrightarrow{\alpha} \).

Clearly \( \xrightarrow{\beta \eta \alpha} \) generates the equality of \( \lambda \eta A \).

The following notation is used in order to facilitate the computation of the
reduction tree of \( Bx \).

4.5 Def. \( \square := Bx \equiv \omega \omega x. \) If \( \Delta \) is a term, then
\( 1\Delta := ((\lambda x . z \Delta)x) \) and \( o\Delta := (\lambda z . z \Delta) \).

4.6 Lemma. \( Bx \xrightarrow{\beta} C(x) \Leftrightarrow C(x) \) has the form \( i_1 \ldots i_n \square \),
\( i_1, \ldots, i_n \in \{0,1\} \) \( (*) \)

Proof.

Note that
(i) Each one step \( \beta \)-reduct of \( o\Delta \) is \( o\Delta' \) where \( \Delta' \) is a one step \( \beta \)-reduct of \( \Delta \).

(ii) Each one step \( \beta \)-reduct of \( 1\Delta \) is \( o\Delta \) or \( 1\Delta' \) where \( \Delta' \) is a one step \( \beta \)-reduct of \( \Delta \).

(iii) The only one step \( \beta \)-reduct of \( \square \) is \( 1\square \).

From (i)-(iii) it follows that all possible \( \beta \)-reducts of \( \square \) are of the form \( (*) \).
Moreover all terms of the form \( (*) \) are reducts of \( \square \) \( \Box \)

4.7 Cor. Let \( Bx \xrightarrow{\beta} C(x) \). Then

(i) \( C(x) \) has no \( \eta \) or \( \Omega \) reducts.

(ii) The only free variable in \( C(x) \) occurs at the end.

(iii) \( C(n) \xrightarrow{\beta} Z \Rightarrow Z = C'(n) \) with \( Bx \xrightarrow{\beta} C'(x) \).

(iv) \( C(x) \equiv \lambda c.P \Rightarrow P \equiv cQ \) and \( Bx \xrightarrow{\beta} Q \).

Proof.
Immediate. \( \Box \)

4.8 Lemma. \( \xrightarrow{\alpha} \) has the CR property.

Proof.
Let two terms be obtained from some term \( M \) by replacing some \( n \) by \( o \). Hence a common reduct \( P \) can be found by making both changes in \( M \). \( \Box \)
4.9 Lemma. \( \frac{\*}{\beta n A} \) is CR.

Proof.

By 4.8 and 4.3 \( \frac{\*}{\beta n A} \) are CR. So by the lemma of Hindley-Rosen, [5](1.2), it is sufficient to prove that they commute. For this it is sufficient to prove

(i) \[
\begin{array}{c}
\text{M} \\
\beta \\
\Lambda \\
\end{array}
\]

(ii) \[
\begin{array}{c}
\text{M} \\
\Delta \\
\Lambda \\
\end{array}
\]

(iii) \[
\begin{array}{c}
\text{M} \\
\eta \\
\Lambda \\
\end{array}
\]

(i) Let \( R \equiv (\lambda z. V) W \) be the \( \beta \)-redex contracted in \( \frac{\*}{A \to L} \) and \( C(n) \) the "A-redex" in \( \frac{\*}{A \to L} \).

Case 1, \( R \cap C(n) = \emptyset \), is trivial.

Case 2, \( R \subseteq C(n) \). By 4.7 (iii) we are done.

Case 3, \( C(n) \subset R \). 3.1: \( C(n) \subset W \), is easy. 3.2: \( C(n) \subset V \): since \( C(n) \) is closed this case is trivial. 3.3: \( C(n) \equiv \lambda z. V \). By 4.7 (iv)

\[
C(n) \equiv \lambda z. z C'(n) \quad \text{where} \quad C'(x) \in \text{Red}(Bx); \quad \text{hence} \quad N \equiv \ldots WC'(n) \ldots, \quad L \equiv \ldots C(o)W \ldots \equiv \ldots (\lambda z. z C'(o))W \ldots \quad \text{Take} \quad P \equiv \ldots WC'(o) \ldots
\]

(ii) Let \( H \equiv \Omega \)-redex and \( C(n) \) the A-redex in M.

Case 1, \( H \cap C(n) = \emptyset \), is trivial.

Case 2, \( H \subseteq C(n) \), does not occur, by 4.7 (i).

Case 3, \( C(n) \subset H \); \( H \equiv H'[C(n)] \), \( M \equiv \ldots H \ldots, N \equiv \ldots \emptyset \ldots, L \equiv \ldots H'[C(o)] \ldots \)

Claim: \( H'[C(o)] \) is unsolvable. So take \( P \equiv N \) to complete the diagram.

Proof of claim (see [2] for the concepts of Bohm-tree and solvably equivalence).

\( C(n) \) and \( C(o) \) have the same Bohm-tree, hence are solvably equivalent, i.e.

for every context \( D[ ] \) we have:

\( D[C(n)] \) is unsolvable \( \iff \) \( D[C(o)] \) is unsolvable.

Now take \( D[ ] \equiv H'[ ] \).

(iii) Let \( E \equiv \lambda x.F(x) \) be the \( n \)-redex and \( C(n) \) be the A-redex in M.

Case 1, \( E \cap C(n) = \emptyset \), is trivial.

Case 2, \( E \subseteq C(n) \), does not occur, by 4.7 (i).

Case 3, \( C(n) \subset E \); 3.1: \( C(n) \equiv F \) cannot occur by 4.7 (ii).

3.2: \( C(n) \subset F \): easy. \( \square \)

4.10 Lemma. For \( n \notin A \), \( n \neq o \), \( \frac{\*}{A \to B} \)

Proof.

If the equation were provable there would be a term \( Z \) s.t. \( \frac{\*}{B \to Z} \) and \( \frac{\*}{B \to Z} \) By 4.7 (ii) it would follow that \( n \) and \( o \) would occur at the same place in \( Z \). \( \square \)
4.11 Cor. Let $o \not\in A$, $A' \subseteq \omega$ and $A \neq A'$. Then
\[ K \eta A \neq K \eta A'. \]

Proof.
Let $n \in A$ but $n \notin A'$, say. Then
\[ K \eta A \vdash B_n = B_0 \quad \text{and} \quad K \eta A' \nvdash B_n = B_0 \] by 4.10. □

4.12 Theorem. There are $2^\aleph_0$ theories between $K \eta$ and $K^*$.

Proof.
By 4.10 each $K \eta A$ is consistent, hence $C K^*$ by [2], 4.8. The result follows from 4.11. □

4.13 Cor. (i) There are $2^\aleph_0$ sensible hard models.

(ii) There are $2^\aleph_0$ sensible extensional models.

Proof.
Note that for $\lambda$-theories $T,T'$
\[ M^{(0)}(T) = M^{(0)}(T') \iff T = T'. \]
The results follow by taking closed respectively open term models. □

§5. Applications of Gross-reduction.

In the preceding paragraphs we have postponed some technicalities, viz. the proofs of
1. $K \eta \nvdash H \times o = H \times o$ where $H$ is a term s.t. $H \times n \xrightarrow{\beta} [I, F_n(H \times n+1)]$
   and $F_n \xrightarrow{\beta} I$ for all $n$.
2. $K \eta \nvdash O \times o = O \times o$ where $O$ is s.t. $O \times n \xrightarrow{\beta} \lambda z. z \times o \times n (O \times n+1)$
3. $K \eta \nvdash A x = A I$ where $A$ is s.t. $A \times \xrightarrow{\beta} \lambda z. A (x \times o))$.

In all three cases the proof is similar: if an equation were provable, the terms would have a common reduct by the Church-Rosser theorem for $K \eta$.
In order to prove that this is impossible one wants to show that the first term has in each reduct the free variable $x$ (and it is clear that for no reduct of the second term $x$ occurs freely in it).
The verification of the last statement is still quite intricate, since the reduction trees of the terms involved are quite complicated due to many detour reductions. To overcome this difficulty we use the concept of a (deterministic) Gross-reduction chain which is cofinal in the reduction tree.
This cofinality enables us to reduce properties of the whole reduction tree to the more easily computable Gross-reduction chain.
5.1 Def. The Gross-contraction of a term $M$, notation $M^*$, is the complete reduction of $M$ w.r.t. all of its redices.

In [3] it is shown that this definition makes sense for $\mathcal{M}_n$.

The Gross-reduction-chain of $M$ is the sequence $(M)_0 = M$, $(M)_{n+1} = (M)^*_n$.

5.2 Lemma. For $\mathcal{M}_n$ the Gross-reduction-chain of $M$ is cofinal in the reduction tree of $M$.

Proof. See [3].

5.3 Proof of 1, 2, 3.

1. Define $[H \times o]^n = [I, [I, ..., [I, H \times n]]...]$. Simple but tedious calculation shows: $(H \times o)^n \xrightarrow{\beta} [H \times o]_m$ for some $m$. (*)

Now $\lambda \beta \eta \Omega \vdash H \times o = H \eta o$. Suppose not, then by (5.2), (5.3), (*) we have:

$x \in \text{FV}([H \times o]_m)$, hence

$x \in \text{FV}(H \eta o)$, contradiction.

2. Define $[O \times o]^n = \lambda y.y(y\Omega(y\Omega(...(y\Omega(0 \times n+1)...)))$. Then

$(O \times o)^n \xrightarrow{\beta} [O \times o]_n$ as direct computation shows.

The rest of the proof is entirely analogous to that of 1.

3. $A_x \equiv \omega \omega x, \omega \equiv \lambda a x.z(a(a(x\eta)))$.

Define $[A x]^n = \lambda z.z(\lambda z.z(...(\lambda z.z(\omega(o(x^n\eta))))...))$. A simple calculation shows $(A x)^n \xrightarrow{\beta} [A x]_n$. The rest of the proof is (almost) analogous to that of 1.
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CHAPTER II
SOME NOTES ON LAMBDA REDUCTION

Introduction. In sections 1 and 2 the Church-Rosser theorem is proved for the \( \lambda^0 \) - respectively \( \lambda_{\beta\eta}(\Omega) \)-calculus.

To add another proof of this theorem needs some motivation, especially since for the \( \lambda^0 \)-calculus there is a shorter one due to Tait and Martin-Löf (see [1]), which can be extended to the \( \lambda_{\beta\eta} \)-calculus using the lemma of Hindley-Rosen, see [9].

For the \( \lambda_{\beta} \)-calculus a proof of the Church-Rosser theorem is given in [7], via the finite developments (FD) theorem, which idea goes back to Curry, see also [6]. As a byproduct [6] shows the possibility of defining Gross-reduction and its cofinality.

We prove the FD theorem using a labeling of variables. This method applies also to the \( \lambda_{\beta\eta}(\Omega) \)-calculus, which is the extension of the theory obtained by adding extensionally (and equating all unsolvable terms).

Now the motivation of the first three sections of this paper is that it gives a straightforward proof of the FD theorem which works for all theories considered. Secondly, we establish the cofinality of Gross-reduction for the \( \lambda_{\beta\eta}(\Omega) \)-calculus, which result was used in [2].

In section 4 we consider reduction strategies; i.e. functions that assign to a term one of its reducts. We distinguish various kinds of strategies, and some known strategies are classified accordingly. Furthermore the (non)existence of certain kinds of (recursive) strategies is proved.

In section 5 we prove that there exists a recursive strategy that finds an infinite reduction sequence if it exists.

In section 6 we prove by one method two theorems in [4], [5], viz. the postponement of \( \eta \)-reductions and the fact that \( \beta \) - and \( \beta\eta \)-normalizibility are the same.

Finally in section 7 some non-normalizing \( S \)-terms are constructed.
1. THE CHURCH-ROSSER THEOREM FOR THE $\lambda\beta$-CALCULUS.

1.0. The finite developments (FD) theorem states that for any set of redices in a term $M$, all developments of $R$ are finite. See [6] for terminology.

We formulate and prove FD using underlined and labeled terms. The underlining specifies and keeps track of a set $R$ of redices. The labeling is used to prove that underlined terms strongly normalize.

1.1. Def. $\text{lab.}^{A}A^{\beta}$ is the set of labeled and underlined $\lambda$-terms, defined by:

1. $x^n \in \text{lab.}^{A}A^{\beta}$ for every variable $x$ and every $n > 1$.
2. $M \in \text{lab.}^{A}A^{\beta} \implies \lambda x. M \in \text{lab.}^{A}A^{\beta}$
3. $M, N \in \text{lab.}^{A}A^{\beta} \implies MN \in \text{lab.}^{A}A^{\beta}$ and $(\lambda x. M)N \in \text{lab.}^{A}A^{\beta}$

Remark that only variables not preceded by $\lambda$ are labeled.

1.2. Def. $\underset{\text{lab.}^{A}A^{\beta}}{\lambda x. M} \rightarrow$ is one step underlined $\beta$-reduction between terms $\in \text{lab.}^{A}A^{\beta}$ defined by

$$C \left[ (\lambda x. M)N \right] \longrightarrow_{\text{lab.}^{A}A^{\beta}} \quad C \left[ [N|x] M \right],$$

where $N, M \in \text{lab.}^{A}A^{\beta}, C[ ] \in \text{lab.}^{A}$ is a context with one hole, and $[ ]$ is the substitution-operator defined by $[N|x] x^n = N$ and the usual other rules.

Remark that $\beta$-redices whose head-$\lambda$ is not underlined, are not allowed to contract.

1.3. Def. The same system without labels will be called $\lambda A^{\beta}$, the corresponding reduction $\rightarrow_{A^{\beta}}$. 
1.4. Def. Let $M \in \text{lab.}\lambda \alpha$ and $N \subseteq M$ ($N$ is subterm of $M$). Then:
\[ |N| = \text{sum of the labels occurring in } N \]
Remark that $|N| > 0$.

1.5. Def. Let $M \in \text{lab.}\lambda \alpha$. The labeling of $M$ is called decreasing iff for every $\beta$-redex $(\lambda x. P)Q$ in $M$ we have $|x| > |Q|$ for all $x \in P$.
Example: $(\lambda x. x^6 x^7)(\lambda x. x^2 x^3)$ is decreasingly labeled, but $(\lambda x. x^4 x^7)(\lambda x. x^2 x^3)$ is not.

1.6. Lemma. Let $M \in \lambda \alpha$. Then there is a decreasing labeling for $M$.
Proof: number the occurrences in $M$ of variables from right to left, starting with 1. Give the $n$-th occurrence the label $2^n$.
Example: if $M = xy((\lambda z. z)x)$ the result is $x^1 y^3 ((\lambda z. z^4)x^2)$. Obviously this is a decreasing labeling, since $2^n > 2^{n-1} + \ldots + 2$. \[ \square \]

1.7. Lemma. Let $M \in \text{lab.}\lambda \alpha$, such that $M$'s labeling is decreasing, and let $M \xrightarrow{\text{lab.}\lambda \alpha} N$. Then (i) $|M| > |N|$

(ii) $N$'s labeling is again decreasing.
Proof of (i). Let $(\lambda x. P)Q$ be the $\bar{\beta}$-redex contracted in $M \rightarrow N$. Each $x \in P$ is replaced by $Q$; since $|x| > |Q|$ this means that the sum of the labels in the contractum is getting less. Also if $P$ contains no $x$ this holds, since $Q$ vanishes and $|Q| > 0$. \[ \square_{(i)} \]

Proof of (ii). Let $(\lambda x'. P')Q'$ be the $\bar{\beta}$-redex of whose residuals we must check that they satisfy the condition for a labeling to be decreasing. For the numbering of the cases, see the cases 11.. in the scheme of relative positions of redices.
Of the cases 11... (all the other cases are for use in section 2) only two are not trivial:

1121 \( M = \ldots (\lambda x \cdot x \ldots (\lambda x'. P'(x)) Q'(x) \ldots) Q \ldots \)

\[ \downarrow \]

\( N = \ldots Q \ldots (\lambda x'. P'(Q)) Q'(Q) \ldots \)

(Here \( Q'(Q) = [Q|x] Q' \))

Since \(|x| > |Q|\) for all \( x \in P \), \(|Q'(Q)| < |Q'|\). Also \(|x'| > |Q'|\) for all \( x' \in P' \). Hence \(|x'| > |Q'(Q)|\) for all \( x' \in P' \).

1142. \( M = \ldots (\lambda x'. P') \ldots (\lambda x. P(x)) Q \ldots \ldots \) where \( \square = Q' \)

\[ \downarrow \]

\( N = \ldots (\lambda x'. P') \ldots P(Q) \ldots \ldots \) where \( \square = Q'' \)

Now \(|(\lambda x. P(x))Q| > |P(Q)|\), so \(|Q'| > |Q''|\), hence in \( N \) for all \( x' \in P' \) we have \(|x'| > |Q'|\).

\( \Box \)
If $M \in \mathcal{A}$, then every $\beta$-reduction sequence starting with $M$ terminates.
Proof. By 1.6 and 1.7 since in a reduction labels can be taken along.

1.9. Def. Let $\rightarrow$ be an arbitrary binary relation. Then
(i) $\rightarrow^{*}$ is the transitive and reflexive closure of $\rightarrow$.
(ii) $\# \rightarrow^{*} \#$ is the transitive closure of $\rightarrow$.
(iii) $\rightarrow$ has the Church-Rosser property (is CR) iff

(iv) $\rightarrow$ has the weak Church-Rosser property (is weakly CR) iff

(v) if $M \rightarrow N$, $N$ will be called a successor of $M$.
(vi) an endpoint is a point without successors.
(vii) $M$ has an endpoint $N$ iff $M \rightarrow \rightarrow N$ where $N$ is an endpoint.

1.10. Lemma. $\rightarrow^{\#} \rightarrow^{*}$ is weakly CR.
Proof: A trivial analysis of a few cases, using
$M \rightarrow^{\#} M' \, , \, N \rightarrow^{\#} N' \Rightarrow [N|x]M \rightarrow^{*}[N'|x]M'$.

1.11. Lemma. Let $\rightarrow$ be a reduction relation such that
(1) every reduction sequence terminates and (2) $\rightarrow$ is weakly CR.
Then every term has a unique endpoint.

Proof. (Bar induction)
A term is **bivalent** if $M$ has at least two different endpoints, otherwise **univalent**.

Claim: if $M$ is bivalent, then $M$ has a bivalent successor.

Indeed, let $M \rightarrow M_1 \rightarrow^{*} N_1$ and $M \rightarrow M_2 \rightarrow^{*} M_2'$
be two reduction sequences terminating in different endpoints $M_1', M_2'$, possibly with $M_1 = M_2$.

By the weak CR property there exists a term $N$ such that $M_1 \rightarrow N, M_2 \rightarrow N$. Let $N'$ be an endpoint of $N$. If, say, $M_1$ were univalent,
then $M_1' = N'$, therefore $M_2' \neq N'$, and hence $M_2$ is bivalent, which proves the claim.
By the claim a bivalent term would yield a non-terminating reduction-sequence, contradicting (1). Hence each term is univalent.

1.12. **Cor. (FD').** Let $M \in \lambda \alpha$. Then every maximal $\beta$-reduction sequence starting with $M$, terminates in a unique result $N$, which will be called the complete reduct of $M$.

1.13. **Notation.** (i) If $M' \in \lambda \beta$ we will also write $M' = (M, \mathcal{U})$ where $M \in \lambda$ and $\mathcal{U}$ is the underlining of $M$, i.e. the set of occurrences of $\lambda$.

(ii) $(M, \emptyset)$, where $\emptyset$ is the empty underlining, will be identified with $M \in \lambda$. ($M \in \lambda$ means: $M$ is a $\lambda$-term, without underlining.)

(iii) If $N = (N, \emptyset)$ is the complete reduct of $(M, \mathcal{U}) \in \lambda \beta$, we will write $(M, \mathcal{U}) \xrightarrow{\text{cpl}} N$.

1.14. **Coroll.** $(M, \mathcal{U})$  

\[ (M', \mathcal{U}) \xrightarrow{\beta} (M, \mathcal{U}) \xrightarrow{\text{cpl}} N \]

**Proof:** 1.12.

1.15. **Def.** (i) $(N, \mathcal{U}) \succeq (N, \mathcal{U}')$ iff $\mathcal{U}' \subseteq \mathcal{U}$.

(ii) $(N, \mathcal{U}) + (N, \mathcal{U}') = (N, \mathcal{U} \cup \mathcal{U}')$

1.16. **Lemma.** $(N, \mathcal{U})$

\[ (M', \mathcal{U}') \xrightarrow{\beta} (N, \mathcal{U}''') \]

**Proof:** it is sufficient to consider the case where $(M, \mathcal{U}') \xrightarrow{\beta} (N, \mathcal{U}'')$ is one step; and for this case the lemma is trivial.
1.17. Def. Let $M, N \in \lambda$. Then
\[ M \xrightarrow{1} N \iff (M, \mathcal{U}) \xrightarrow{\text{cpl}} N \text{ for some underlining } \mathcal{U} \text{ of } M. \]

Remark that $\xrightarrow{1} \supseteq \xrightarrow{\beta}$ (the usual one step $\beta$-reduction between $\lambda$-terms). This follows by considering the underlining of just one $\beta$-redex.

1.18. Lemma.

Proof.
\[ \begin{align*}
\text{a: } & \text{lemma 1.16.} \\
\text{b: } & \text{coroll. 1.14.} \\
\text{c: } & \text{def. 1.17.}
\end{align*} \]

1.19. Lemma. \( \xrightarrow{1} \) is CR.

Proof:
\[ \begin{align*}
\text{a, a': } & \text{def. 1.17.} \\
\text{b: } & \text{def. 1.15.} \\
\text{c, c': } & \text{lemma 1.18.}
\end{align*} \]

1.20. Theorem (CHURCH - ROSSER): \( \xrightarrow{\ast} \) is CR.

Proof. \( \xrightarrow{\beta} \subseteq \xrightarrow{1} \) (see remark at 1.17) and \( \xrightarrow{1} \subseteq \xrightarrow{\ast} \), hence \( \xrightarrow{\beta} = \xrightarrow{\ast} \).

\( \xrightarrow{1} \) is CR, hence \( \xrightarrow{\ast} \) is CR. \( \Box \)
2. THE CHURCH-ROSSER THEOREM FOR THE \( \lambda\beta\eta(\Omega) \)-CALCULUS

2.0. Introduction. The concept of underlining and underlined reduction in the \( \lambda\beta \)-calculus generalizes directly to the \( \lambda\beta\eta \)-calculus, so we want to use the method of section 1 for the \( \lambda\beta\eta \)-calculus. But then there is a problem when one tries to define the analogon of \( \rightarrow \); using the method of the labels as in section 1, the FD theorem is still valid, but 1.10 fails, as is shown by the example in [4] p. 119:

Here \( \_ \) denotes a specified \( \beta \)-redex and \( \_ \) a specified \( \eta \)-redex, in our notation.

That FD is still valid can be easily verified, but we will not do this because by a simple restriction (on what sets of specified redices, i.e. what underlinings, are allowed) we have moreover FD\(^+ \) (see 1.12) for the \( \lambda\beta\eta \)-calculus.

\( \mathcal{K} \) is the \( \lambda \)-theory in which all unsolvable terms are equated. As with ordinary conversion, it is useful to have a reduction relation satisfying the Church-Rosser theorem which generates equality in \( \mathcal{K} \). This will be \( \beta\eta\Omega \)-reduction which is defined by adding \( \Omega \)-contraction defined by

\[
C[H] \rightarrow^\Omega C[\Omega],
\]

where \( \Omega = (\lambda x. xx)(\lambda x. xx) \) and \( H \) is unsolvable.

The CR theorem is proved first for a restricted form of \( \Omega \)-reduction (the \( \Omega \)-redices have to be maximal w.r.t. inclusion of subterms; this is called \( \Omega ' \)-reduction) from which the theorem is proved for the general form. While \( \beta \)- and \( \eta \)-redices interfere in a nasty way, there is no interference of \( \lambda \)-, \( \eta \)-redices and \( \Omega ' \)-redices.

The CR theorem for the \( \lambda\beta\eta \)-calculus can be proved more easily than below by using the lemma of Hindley-Rosen [9] 1.2.

The benefit of the method here is that it gives an easy proof for the theorems in section 3.
2.1. Def. (i) To the language of the lab. $\lambda \eta$ -terms we add an extra symbol $\sim$, which will be used to indicate $\eta$-redices, relative to which $\eta$-reduction is allowed. $\sim$ will be written under the head $-\lambda$ of an $\eta$-redex: $\lambda y. M y$ ($y \notin FV(M)$)

Formally: extend def. 1.1 with the extra rule for term-formation:

4. $M \in \text{lab. } \lambda \eta \quad \Rightarrow \quad \lambda y. M y \in \text{lab. } \lambda \eta$ ($y \notin FV(M)$)

$\lambda \eta$ is the corresponding set of terms without labels.

Remark. In a (lab.) $\lambda \eta$-term a $\lambda$ can be underlined with $\sim$ if it is a $\beta$-redex $\lambda$ and with $\sim$ if it is an $\eta$-redex $\lambda$, but no $\lambda$ can be underlined by both $\sim$ and $\sim$.

2.2. Def. Let $M, N \in \lambda \eta$. Then $M \xrightarrow{\beta} N$ is defined as follows.

Let $(\lambda x. P)Q \subseteq M$ be the $\beta$-redex to reduce.

Case 1. $M \equiv C[\lambda y. (\lambda x. P(x))y]$, i.e. $Q \equiv y, y \notin FV(P)$, and $C[\ ]$ is some context (with one hole). Then

$$M \xrightarrow{\beta} C[\lambda y. P(y)]$$

Case 2. If not case 1, then

$$M \equiv C[(\lambda x. P(x))Q] \xrightarrow{\beta} C[P(Q)]$$

2.3. Def. Let $M, N \in \lambda \eta$. Then $M \xrightarrow{\eta} N$ is defined as follows.

Let $\lambda y. D y \subseteq M$ be the $\eta$-redex to reduce.

Case 1. $M \equiv C[\lambda y. (\lambda x. P)y]$, i.e. $D y \equiv (\lambda x. P)y, y \notin FV(P)$, and $C[\ ]$ some context. Then

$$M \xrightarrow{\eta} C[\lambda x. P]$$

Case 2. If not case 1, then

$$M \equiv C[\lambda y. D y] \xrightarrow{\eta} C[D]$$
2.4. Def. \[ \text{lab.}_2 \rightarrow \] and \[ \text{lab.}_2 \rightarrow \] are the corresponding reduction relations in the presence of labels.

2.5. Remark. The underlinings and underlined reductions formalize the same concept of residual of \( \beta \)- and \( \eta \)-reduces as in [4] page 117, 118.

2.6. Def. (i) Let \( M \in \lambda \) and \( N \subseteq M \). The subterm \( N \) is a maximal unsolvable

subterm iff 1. \( N \) is unsolvable

and 2. (all \( L \)) \( N \subseteq L \subseteq M \) & \( L \) unsolvable \( \Rightarrow N = L \).

(ii) \( (\text{lab.})\lambda \beta \eta \nu^{-1} \) is \( (\text{lab.})\lambda \beta \eta \) where maximal unsolvable subterms can be underlined with a dot-line \( \cdots \cdots \). Such underlined maximal unsolvable subterms will be called \( \nu \)-reduces.

(iii) \[ \text{lab.}_1 \rightarrow \], one step \( \nu \)-reduction in \( \lambda \beta \eta \nu \), is defined by

\[ \text{lab.}_1 \rightarrow \]

where \( \nu = (\lambda x. xx)(\lambda x. xx) \) and \( c[\ ] \) is some context with one hole.

\( \text{lab.}_1 \rightarrow \) is the corresponding reduction in \( \lambda \beta \eta \nu \) defined by

\[ \text{lab.}_1 \rightarrow \]

where \( \nu = (\lambda x. x^4 x^4)(\lambda x. x^4 x^4) \) and \( c[\ ] \) is some context in \( \lambda \beta \eta \nu \).

2.7. Def. Extension of (i) \[ \text{lab.}_2 \rightarrow \], (ii) \[ \text{lab.}_2 \rightarrow \] from \( \text{lab.}_2 \rightarrow \) to \( \text{lab.}_2 \rightarrow \).

(i) Let \( M' \in (\text{lab.})\lambda \beta \eta \nu \), then \( M' \) can be considered as a pair \( (M, U) \)

where \( M \subseteq (\text{lab.})\lambda \beta \eta \) and \( U \) is the set of occurrences of \( \nu \)-reduces.

Let \( M \rightarrow \) \( N \), and let \( V \) be the set of descendants of the subterms in \( U \). (Here the concept of descendant is in a natural way suggested by keeping track of underlinings during the reduction.)
Further, let \( W \) be the set of maximal unsolvable subterms of \( N \) generated by \( V \) as follows: \( H \in W \iff 1. \) \( H \) is maximal unsolvable subterm and \( 2. \exists L \subseteq H \) such that \( L \in V. \)

Now define \( \frac{M, \gamma}{(\text{lab.})_\gamma} \) in \( \frac{(\text{lab.})_\lambda}{\text{lab.}} \) by

\[
\frac{M, \gamma}{(\text{lab.})_\lambda} \rightarrow (N, \omega). \]

Example: \( \frac{(\lambda x. x(\Omega x))}{(\text{lab.})_\gamma} \rightarrow \Omega(\Omega \Omega) \)

(ii) Similar definition for \( \frac{M, \gamma}{(\text{lab.})_\lambda} \) in \( \frac{(\text{lab.})_\lambda}{\text{lab.}} \). (Remark: in this case \( V = W \))

2.8. Def. \( \frac{(\text{lab.})_\lambda^2}{(\text{lab.})_\gamma^1} \rightarrow \frac{(\text{lab.})_\lambda}{(\text{lab.})_\gamma} \rightarrow \frac{(\text{lab.})_\lambda}{(\text{lab.})_\gamma} \rightarrow \frac{(\text{lab.})_\lambda}{(\text{lab.})_\gamma} \rightarrow \frac{(\text{lab.})_\lambda}{(\text{lab.})_\gamma} \)

2.9. Def. Let \( M \in \frac{(\text{lab.})_\lambda}{(\text{lab.})_\gamma} \). Again, \( M \)'s labeling is called decreasing if all its \( \Omega \) -redices \( (\lambda x. P)Q \) are decreasingly labeled, i.e. for all \( x \in P: |x| > |Q|. \)

2.10. Lemma. Let \( M \in \frac{(\text{lab.})_\lambda}{(\text{lab.})_\gamma} \). Then there is a decreasing labeling for \( M. \)

Proof: same as of lemma 1.6. \( \square \)

2.11. Lemma. Let \( M \in \frac{(\text{lab.})_\lambda}{(\text{lab.})_\gamma} \), such that \( M \)'s labeling is decreasing, and let \( M \frac{(\text{lab.})_\gamma}{(\text{lab.})_\lambda} \rightarrow N. \) Then (i) \( |M| > |N| \)

(ii) \( N \)'s labeling is again decreasing.

Proof of (i). In \( M \frac{(\text{lab.})_\gamma}{(\text{lab.})_\lambda} \rightarrow N \) is contracted 1) a \( \beta \) -redex, 2) an \( \eta \) -redex, or 3) an \( \Omega \) -redex.

Case 1) was considered in the previous section.

2) Let the \( \eta \) -redex be \( \lambda y. D_y^k, y \notin \text{FV}(D). \) Then

\[
|\lambda y. D_y^k| = k + |D| > |D| \text{ since } k > 0. \]
3) Let $H$ be this $\bigwedge$-redex. Then $H \xrightarrow{\bigwedge} (\lambda x. x' x)(\lambda x. x' x')$.

A simple analysis shows that if $H$ is unsolvable, then $H \equiv \Omega$, containing 4 variables, or $H$ contains more than 4 variables.

In the latter case, $|H| > 5$, since the labels are $\geq 1$; so indeed $|H| > |\text{contractum of } H|$.

In the former case, trouble seems to arise when $H \equiv (\lambda x. x' x)(\lambda x. x' x)$ but this case does not occur since the labels in the initial labeling, i.e. the labeling in the preceding lemma, are $\geq 2$.

Hence if a label of some $x$ is 1, then $x$ occurs in $(\lambda x. x' x')(\lambda x. x' x')$ which can only be a contractum of an $\bigwedge$-redex and has therefore no underlining. $\Box (i)$

Proof of (ii). We have to check that all residuals of the $\beta$-redices in $M$ are again decreasingly labeled. To do this we use the first row of the scheme of relative positions of redices, i.e. the cases $1...$. Here $R$, $E$ or $H$ are the redices contracted in $M \xrightarrow{\bigwedge} N$, and $R'$ is the $\beta$-redex in $M$ whose residuals in $N$ we have to check. Only the non-trivial cases will be mentioned.

Case 1222. Remark that $R'$ has no underlined residual:

$\lambda y. Dy \equiv \lambda y. (\lambda x'. P') y \xrightarrow{\bigwedge} \lambda x'. P'$

1232 does not occur, since $\sim$ and $\sim$ are not allowed to coincide.

1233. Here $Q' \equiv C[E]$ for some context $C[\ ]$. Now if $x' \in P'$, then $|x'| > |C[E]|$ by the hypothesis of the lemma, and $|E| > |D|$, hence in the residual of $R'$: $|x'| > |C[D]|$, so this $\beta$-redex is again decreasingly labeled.

132, 133. $R'$ has no underlined residual.

1342 does not occur, since $\lambda x', P'$ is not maximal unsolvable.

1343. Let $Q' \equiv C[H]$ Now if $x' \in P'$ then $|x'| > |C[H]| > |C[\Omega]|$.
2.12. Coroll. If \( M \in \lambda \eta \Omega' \), then every \( \beta \eta \Omega' \) reduction sequence starting with \( M \) terminates.

Proof. By 2.10 and 2.11 since in a reduction labels can be taken along. □

2.13. Lemma. \( \xrightarrow[\beta \eta \Omega']{} \) is weakly CR, i.e.:

![Diagram]

Proof. See the scheme of relative positions of redices. Let \( R', E', H' \) be the redex contracted in \( M \xrightarrow[\beta \eta \Omega']{} N \) and \( R, E, H \) the redex contracted in \( M \xrightarrow[\beta \eta \Omega']{} L \). Only the non-trivial cases will be mentioned.

The cases 11.. are analogous to the corresponding cases in §1.

Case 1222. \( M = C[\lambda y. (\lambda x'. P'(x'))y] \) where \( C[\ ] \) is some context, \( N = C[\lambda y. P'(y)] \) and \( L = C[\lambda x'. P'(x')] \). Take \( P \equiv N \equiv L \).

Case 1232. \( M = C[(\lambda y. Dy)Q'] \). However, \( \lambda \) and \( \sim \) are not allowed to coincide (see 2.1.(1)), so this case does not occur.

132, 133. Notice that the set of unsolvables is closed under \( \beta \) reduction.

232, 233. Notice that the set of unsolvables is closed under \( \eta \) reduction. 1341 and 2341 follow by 2.29(3).

1342, 2342, 332 and 334 do not occur because an \( \Omega' \) redex is defined as a maximal unsolvable subterm. □

2.14. Coroll. Let \( M \in \lambda \eta \Omega' \). Then every maximal \( \beta \eta \Omega' \) reduction sequence starting with \( M \) terminates in a unique result, which will be called the complete reduct of \( M \).

Proof. 2.12, 2.13 and 1.11. □

2.15. Notation. Analogon of 1.13 for \( \lambda \eta \Omega' \) and \( \xrightarrow[\beta \Omega']{} \) in stead of \( \xrightarrow[\beta \Omega]{} \) and \( \xrightarrow[\beta \Lambda]{} \). \( U \) is now a triple consisting of a set of occurrences of \( \Lambda \), a set of \( \Lambda' \)'s, and a set of maximal unsolvable subterms.
2.16. **Coroll.** Analogous to coroll. 1.14.

2.17. **Def.** Let \( M, N \in \lambda \). Then \( M \rightarrow N \leftrightarrow (M, U) \rightarrow_{cpl} N \) for some underlining \( U \) of \( N \).

2.18. **Remark.** Up to here we generalized the reduction \( \rightarrow \) from the \( \lambda \beta \) - to the \( \lambda \beta \eta \) -calculus. The next step, as in §1, is to prove that \( \rightarrow \) is CR. In §1 this was done by taking the union of two underlinings of \( M \). In the present case this would result in coincidences of \( \_ \) and \( \_ \) (i.e. \( \_ \) ) which is forbidden; hence the definition of a 'union' of two underlinings requires more consideration.

Suppose we are given a \( \lambda \)-term with an underlining in which two lines (\( \_ \) or \( \_ \) ) occur. These two lines allow two reduction-steps; except in the following case: \( \ldots \lambda y. (\lambda x. M)y \ldots \)

This motivates the definition of a chain and its energy.

2.19. **Def.** (i) Let \( \lambda_1, \lambda_2 \) be two occurrences of \( \lambda \) in \( M \in \lambda \).

\( \lambda_1 \) and \( \lambda_2 \) are **connected**, written \( \lambda_1 \sim \lambda_2 \), iff they occur in a context \( \lambda_1.x. (\lambda_2.y. N)x \) for some \( N \) such that \( x \notin FV(N) \).

(ii) A **maximal** sequence of connected \( \lambda \)'s is called a chain.

The length of the chain is its number of \( \lambda \)'s.

Example:

\[
\lambda a.(\lambda b.(\lambda c. (\lambda d. N)c)b)a
\]

(iii) A non-connected \( \lambda \) forms a chain on its own.

2.20. **Notation.** Let \( M \in \lambda \). Then \( (M)_0 \equiv M \)

\[
(M)_{n+1} \equiv \lambda x. (M)_n x \text{ where } x \notin FV((M)_n).
\]

2.21. **Remark.** Sometimes we will identify a chain of length \( n+1 \) with its corresponding \( \lambda \)-term, which can be written as \( (\lambda a.A)_n \), where \( n > 0 \), \( (\lambda a.A)_n \) does not occur in a context \( \lambda b.(\lambda a.A)_n b \), and \( A \neq (\lambda a'.A')_n \).
2.22. Def. Let \((C, \mathcal{U})\) be a chain with underlining \(\mathcal{U}\). The **energy** of \((C, \mathcal{U})\), \(\| (C, \mathcal{U}) \|\), is the number of occurrences of \(\lambda\) in \((C, \mathcal{U}_{\text{normal}})\) where \(\mathcal{U}_{\text{normal}}\) results from \(\mathcal{U}\) as follows: whenever \(\lambda\) occurs in \((C, \mathcal{U})\) then it is replaced by \(\lambda\). (Remark: it is also possible to delete \(\lambda\) in stead of \(\lambda\).)

2.23. Def. (i) \((M, \mathcal{U}) \leq (N, \mathcal{U}') \iff \| (C, \mathcal{U}) \| \leq \| (C, \mathcal{U}') \|\) for every chain \(C\) in \(M\), and 2. \(\Omega(M, \mathcal{U}) \subseteq \Omega(N, \mathcal{U}')\) where \(\Omega(M, \mathcal{U})\) is the set of occurrences of \(\Omega\)-redexes in \((M, \mathcal{U})\).

(ii) \((M, \mathcal{U}) + (M, \mathcal{U}') = (M, \mathcal{U}''\) where \(\mathcal{U}''\) is some underlining such that 1. \(\| (C, \mathcal{U}''\) \| = \max (\| (C, \mathcal{U}) \|, \| (C, \mathcal{U}') \|)\) for every chain \(C\) in \(M\), and 2. \(\Omega(M, \mathcal{U}''\) = \(\Omega(M, \mathcal{U}) \cup \Omega(M, \mathcal{U}').\)

2.24. Coroll. \((M, \mathcal{U}) + (N, \mathcal{U}') \geq (M, \mathcal{U}), (N, \mathcal{U}').\)

2.25. Lemma. 

![Diagram](image)

Proof. It is sufficient to consider the case that \((M, \mathcal{U}') \xrightarrow{\beta^n\eta^n} (N, \mathcal{U}')\) is one step. There are 3 cases: 1. a \(\beta\)-redex, 2. an \(\eta\)-redex, or 3. an \(\Omega\)-redex is contracted.

Case 1, 2. Consider the chain \(C\) in \((M, \mathcal{U}')\) of which the head-\(\lambda\) of the contracted \(\beta\)- or \(\eta\)-redex is a part. We will distinguish two subcases: a. the length of \(C\) is \(\geq 1\), b. the length of \(C\) is 1.

a. Let \(C = \lambda a_n \ldots \lambda a_1 (\lambda a \cdot (\lambda a) \ldots a)\), \(a_n = (\lambda a \cdot (\lambda a) \ldots a)\), \(n \geq 1\) and let \(\| (C, \mathcal{U}') \| = m' \geq 1\). By def. 2.23, \(\| (C, \mathcal{U}) \| = m \geq m' \geq 1\), hence \((C, \mathcal{U})\) has an underlined \(\lambda\) (\(\Delta\) or \(\Lambda\)). After contraction of such a \(\Delta\) or \(\Lambda\) (it does not matter which underlined \(\lambda\) of the chain is contracted),
the descendant of \( C \) in \((N, \psi)\) is clearly a chain \( C' \) such that 
\[ \| (C', \psi') \| = m-1. \]
Because \[ \| (C', \psi') \| = m'-1 \]
we have indeed \[ \| (C', \psi') \| \geq \| (C', \psi') \|. \] The other chains in \( M \) are clearly not affected by the contraction.

b. In this case there is the problem that new chains can be created, by concatenation of two (or in one case even three) chains.

Example. Let \( C_1 = (\lambda a. za)_n \) and \( C_2 = (\lambda b. B)_m \); then
\[ (\lambda z. C_1) C_2 \rightarrow (\lambda b. B)_{m+1+n}. \]
The problem is as follows: suppose that \( C_1 \equiv \ldots \lambda \ldots \) and \( C_2 \equiv \lambda \ldots \ldots \) concatenate to \( \ldots \lambda \ldots \lambda \ldots \ldots \), then there would be a 'loss of energy' of 1, and the lemma would fail. This situation cannot happen, however.

For suppose \( C_1 \equiv (\lambda a.Aa)_n \) where \( a \not\in \text{FV}(A) \) and \( A \not\equiv \lambda a'. A' \) (\( \Phi \)), and \( C_2 \equiv \lambda b.B \). Then \( C_2 \) must occur in \( (C_2 D) \) for some \( D \). Let \( (\lambda b.B')D' \) be the residual of \( C_2 D \) after the contraction that causes the concatenation.

The concatenated chains must have the form \( (\lambda a. (\lambda b.B')a)_n \). Hence \( D' \equiv a \), but this can only be the case if \( C_1 \equiv (\lambda a. (\lambda b.B)a)_n \), in contradiction with \( \Phi \).

Case 3. Suppose \( H \subseteq (N, \psi') \) is the contracted \( \Omega \)-redex. Let \((N, \psi)\) be the result of the contraction of the homologous \( H \subseteq (N, \psi) \).

Let \( C \subseteq N \) be a chain and let us compare \( \| (C, \psi) \| \) and \( \| (C, \psi') \| \).

By the maximality of \( \Omega \)-redices there are only the following two possibilities: i) \( C \subseteq N \) is the descendant of the 'same' chain in \((N, \psi)\) (although the corresponding subterms can be different),

ii) \( C \) is the result of concatenation of some chains in \((M, \psi)\).

In case i) there is no problem. In case ii) we prove by the same argument as above that there is no loss of energy. \( \Box \)
2.26. **Lemma.** Analogous to lemma 1.18.

2.27. **Lemma.** \( \frac{N_1}{N_2} \) is CR.

Proof: analogous to the proof of 1.19. \( \Box \)

2.28. **Lemma.** \( \frac{\lambda \beta \eta \Omega}{\beta \eta \Omega} \) is CR.

Proof: analogous to the proof of 1.20. \( \Box \)

Now we will prove that \( \frac{\lambda \beta \eta \Omega}{\beta \eta \Omega} \) as defined in 2.0. is CR.

2.29. **Lemma.**

(1) \( \lambda \beta \eta \Omega \models N_1 = N_2 \Rightarrow \exists L \quad N_1 \xrightarrow{\beta \eta \Omega} L \xleftarrow{\beta \eta \Omega} N_2 \)

(2) \( \frac{\beta \eta \Omega \models}{\beta \eta \Omega} \subseteq \frac{\beta \eta \Omega}{\beta \eta \Omega} \)

(3) \( M \xrightarrow{\beta \eta \Omega} M' \Rightarrow \exists L \quad M \xrightarrow{\beta \eta \Omega} L \xleftarrow{\beta \eta \Omega} M' \)

Proof: (1) is the standard reformulation of the Church-Rosser theorem 2.28. (2) follows directly from the definitions.

(3). Let \( \lambda \beta \eta \Omega \) be the \( \Omega \)-redex in \( M \) and let \( H \) be the maximal unsolvable subterm of \( M \) containing \( \lambda \beta \eta \Omega \). Then contraction of \( H \) gives the required \( L \). \( \Box \)

2.30. **Theorem.** \( \frac{\lambda \beta \eta \Omega}{\beta \eta \Omega} \) is CR.

Proof. Suppose that \( N_1 \xleftarrow{\lambda \beta \eta \Omega} \xrightarrow{\lambda \beta \eta \Omega} N_2 \).

Then by 2.29 (3) \( \lambda \beta \eta \Omega \models N_1 = N_2 \) and hence by 2.29 (1) \( N_1, N_2 \) have a common \( \lambda \beta \eta \Omega \)-reduct \( N_3 \).

By 2.29 (2) \( N_3 \) is also a common \( \lambda \beta \eta \Omega \)-reduct of \( N_1, N_2 \).

Hence \( \lambda \beta \eta \Omega \) is CR. \( \Box \)
3. THE COFINALITY OF GROSS-REDUCTION

3.0. For the $b\eta$-calculus the reduction strategy introduced in this section and its cofinality were communicated to us by professor Gross, see also [6]. Due to the result in the previous section we can introduce a similar strategy for the $b\eta(\Omega)$-calculus.

3.1. Gross-reduction in the $b\eta$-calculus.

3.1.1. Def. $\overset{\text{G}}{\rightarrow}$, one step Gross-reduction, is defined by:

$$M \overset{\text{G}}{\rightarrow} N \leftrightarrow (M, \mathcal{U}_{\text{tot}}) \overset{\text{cpl}}{\rightarrow} N$$

where $\mathcal{U}_{\text{tot}}$ is the total underlining of all $\beta$-reduces in $M$.

3.1.2. Lemma. Proof:

The proof is a direct consequence of def. 3.1.1 and 1.17, and lemma 1.18.

3.1.3. Theorem. Proof:

$$\overset{\delta}{\rightarrow} \subseteq \overset{1}{\rightarrow}, \text{ so } \overset{*}{\rightarrow} \subseteq \overset{*}{\rightarrow}$$

$$\overset{1}{\rightarrow} \subseteq \overset{*}{\rightarrow}/\beta, \text{ so } \overset{*}{\rightarrow} \subseteq \overset{*}{\rightarrow}/\beta;$$

hence $\overset{*}{\rightarrow}/\beta = \overset{*}{\rightarrow}/1$

So we have to prove:

and this follows immediately from 3.1.2, 1.19 and a simple diagram-chasing argument as suggested by the figure.
3.2. Gross-reduction in the $\lambda\beta\eta(\forall)$-calculus.

3.2.1. Def. (i) \[ M \xrightarrow{\text{G}} N \] one step Gross-reduction, is defined by:

\[ M \xrightarrow{\text{G}} N \iff (M, \mathcal{U}_{\text{tot}}) \xrightarrow{\text{cpl}} N, \] where

(ii) $\mathcal{U}_{\text{tot}}$, the total underlining, is defined as follows:

a. Underline all maximal unsolvable subterms of $M$ with $\ldots$.

b. Underline all non-connected $\eta$-redex $\lambda$'s with $\sim$.

c. Underline all non-connected $\beta$-redex $\lambda$'s with $\sim$, unless such a $\lambda$ is already underlined by b.

d. If $C \equiv (\lambda a. A) n$ is a chain of length $\geq 2$, we distinguish three cases. 1. $C$ is active, i.e. occurs in a context $(CD)$ for some $D$.

Then the underlining will be $\underline{\lambda} \sim \underline{\lambda} \sim \ldots \sim \underline{\lambda} \sim \underline{\lambda}$.

2. $C$ is not active, and $A \equiv A' a$ for some $A'$ s.t. $a \notin \text{FV}(A')$.

Then the underlining will be $\underline{\lambda} \sim \underline{\lambda} \sim \ldots \sim \underline{\lambda} \sim \underline{\lambda}$.


Then the underlining will be $\underline{\lambda} \sim \underline{\lambda} \sim \ldots$.

In this way we have given each chain in $M$ a maximal amount of energy. Clearly $(M, \mathcal{U}_{\text{tot}}) \supseteq (M, \mathcal{U})$ for all $\mathcal{U}$.

3.2.2. Lemma.

Proof: similar to that of 3.1.2. \( \Box \)

3.2.3. Lemma. Proof: similar to that of 3.1.3. \( \Box \)
3.2.4. Theorem.

Proof. \( M \xrightarrow{\beta \eta \Omega} L \implies \lambda \beta \eta \Omega \models M = L \) by 2.29.(3). By 2.29.(1) \( M \) and \( L \) have a common \( \beta \eta \Omega \)-reduct \( P \). So by 3.2.3, there is an \( N \) such that

By 2.29(2) \( N \) is as required. \( \Box \)
4. **REDUCTION STRATEGIES**

4.1. **Def.** Let $\lambda$ be the set of all $\lambda$-terms.

A *reduction strategy* is a map $F : \lambda \rightarrow \lambda \cup \{\emptyset\}$ such that

(i) $M \xrightarrow{\beta} F(M)$ if $M$ is not in normal form.

(ii) $F(M) = \emptyset \iff M$ is in normal form (nf).

A strategy is a 1-strategy (or one step strategy) if for all $M$ not in nf $M \xrightarrow{\beta} F(M)$. In contrast to standard use $\rightarrow$ is not reflexive.

A strategy is recursive if it is recursive after coding of the terms.

4.2. **Examples** of recursive strategies are

(i) Gross-reduction, defined in 3.1.4.


Note that both strategies only depend on the skeleton of terms. (The skeleton of e.g. $y(\lambda x. xx)$ is $\emptyset(\emptyset \cdot \emptyset \cdot \emptyset)$.)

4.3. **Def.** Let $F$ be a strategy.

(i) $F$ is normalizing if for all $M$ having a nf, $\exists n F^n(M) = \emptyset$.

(ii) $F$ is cofinal if for all $M$ and $N$ such that $M \xrightarrow{\beta} N$, $\exists n N \xrightarrow{\beta} F^n(M)$.

(iii) $F$ is perpetual if for all $M$, $M$ has an infinite reduction sequence $\Rightarrow \forall n F^n(M) \neq \emptyset$.

**Remarks.**

(i) Let $\Delta$ have no nf. Then $K\Delta$ is a term with a normal form which also has an infinite reduction sequence ($K\Delta \xrightarrow{\beta} K\Delta \xrightarrow{\beta} \ldots$). Thus in order to show that a term has no nf it is not sufficient to show that a term $M$ has an infinite reduction sequence. Therefore a normalizing strategy $F$ is useful, since it shows that a term $M$ has no nf if $F$ does not terminate on $M$.

(ii) There are even terms $M$ such that each subterm has a nf, but $M$ does have an infinite reduction sequence, e.g. $PP$, with $P = \lambda z.(\lambda xy.y)(zz)$.

(iii) In 5.18 it is proved that a perpetual strategy cannot depend only on the skeleton of a term.

4.4. **Proposition.** (i) Any cofinal strategy is normalizing. (ii) Gross-reduction is a recursive cofinal strategy. (iii) Normal reduction is a recursive one step strategy.

In the next section a recursive perpetual strategy will be constructed.

4.5. Definition. Let $F$ be a strategy. Then

$$L_F(M) = \mu n. (F^n(M) = \varnothing)$$

$$B_F(M) = \max \{ \text{length}(F^n(M)) : n \in \omega \& k < n \Rightarrow F^k(M) \neq \varnothing \}.$$ 

$L_F(M), B_F(M)$ are possibly $\infty$.

4.6. Def. Let $F$ and $G$ be normalizing strategies.

$$F \preceq_L G \iff \forall M \left[ M \text{ has a nf } \Rightarrow L_F(M) \preceq L_G(M) \right]$$

$$F \preceq_B G \iff \forall M \left[ M \text{ has a nf } \Rightarrow B_F(M) \preceq B_G(M) \right]$$

$F$ is $L(B)$-better than $G$ if $F \preceq_L L(B) G$ and not $G \preceq_L L(B) F$. 

$F$ is $L(B)$-optimal if no strategy is $L(B)$-better than $F$. 

$F$ is $L(B)$-1-optimal if $F$ is a 1-strategy and no 1-strategy is $L(B)$-better than $F$.

4.7. Proposition. There exists

i. an $L$-optimal strategy

ii. a $B$-optimal strategy

iii. no recursive $L$-optimal strategy

iv. no recursive $B$-optimal strategy

v. an $L$-1-optimal strategy

vi. a $B$-1-optimal strategy.

Proof. i, ii are trivial. iii: let $F$ be a recursive $L$-optimal strategy. Then for all $M$ having a nf $F(M)$ is a nf or $\varnothing$, hence $M$ has a nf iff $F(M)$ is a nf or $\varnothing$. This makes 'M has a nf' decidable which is impossible. iv: similar to the proof of thm. 4.8. v and vi are trivial.

4.8. Theorem. There is no recursive $B$-1-optimal strategy.

Proof. Let $\phi$ be a partial recursive function with index $0$ such that the $W_i = \{ x | \phi(x) = i \}$ for $i = 0, 1$ are recursively inseparable.

We can find terms $A_1$ and $A_2$ which have the following properties (which are stated in a very informal way):

i) The terms $A_1 x$ can reduce in at most one way. Their reducts have the same property and so on. Let $(A_1 x)$ be the $n$-th reduct (i.e. $n$ times
one step reduction) of $A_1x$ if it exists.

ii) If $\varphi(x) \neq 0$ and $\varphi(x) \neq 1$ the length of the $(A_1x)^n$ depends as follows on $n$:

\[ lth(A_0x)^n \]

\[ n \rightarrow \]

\[ lth(A_1x)^n \]

\[ n \rightarrow \]

In this case both $A_0x$ and $A_1x$ have no normal form.

iii) If $\varphi(x) = 0$ then the dependence is as follows.

(Let $k$ be the length of the computation $\{e\}(x)$.)

\[ lth((A_0x)^n) \]

\[ n \rightarrow k \]

\[ lth((A_1x)^n) \]

\[ n \rightarrow k \]

Further $(A_0x)^{k+1}$ and $(A_1x)^{k+1}$ are in normal form.

iv) Finally if $\varphi(x) = 1$, then the dependence of $lth((A_1x)^n)$ on $n$ is as in iii) but with the pictures interchanged.

Let $C = \lambda y. y(A_0x)(A_1x)$. Normalizations of $C$ consist just of mixtures of normalizations of $A_0x$ and $A_1x$. Suppose $F$ is a recursive strategy which minimizes breadth. Obviously there exists a recursive $f$ such that $f(x) = 0$ if $F$ says that first $A_0x$ has to be reduced and $f(x) = 1$ if the reduction has to start with $A_1x$.

We claim that $f$ gives a recursive separation of $W_0$ and $W_1$. Suppose $x \in W_1$, then $\varphi(x) = 1$. In this case for some $n, (A_1x)^{n+1}$ is in nf and $lth((A_1x)^{n+1}) = 1$. Further $lth((A_0x)^k)$ 'stabilizes' on a high level. It is clear that the smallest breadth is reached if we first reduce $A_1x$ to a normal form (of length 1) and then $A_0x$. So $f(x) = 1$. Similarly $x \in W_0$ implies $f(x) = 0$. \[ \square \]
4.9. **Theorem.** There is no recursive $L_1$-optimal $L_0$-strategy.

**Proof.** In the same spirit as the proof of the previous theorem, again using a pair of recursively inseparable r.e. sets. □

4.10. **Theorem.** There is no one step strategy which is both $L_1$ and $B_1$ optimal.

**Proof.** Consider the term $Z = (\lambda x. p x x( y I))(\lambda x. p x x A) I$

$$2$$

where $A$ is in nf and very long. We show that if $L_F(Z)$ is minimal, $F(Z)$ must result from $Z$ by a reduction of redex 1, whereas minimalization of $B_F(Z)$ requires first to reduce redex 2. The first fact is obvious as reducing redex 2 first results in duplication of redex 1. On the other hand if we just compare the breadth of normalizations starting with a reduction of 1 and 2 we see that starting with redex 2 minimalizes the breadth. Reduction of 2 yields:

$$(\lambda y. p((\lambda x. p x x A)((\lambda x. p x x A)(y I))) I \quad \frac{\beta}{\beta} \rightarrow$$

$p((\lambda x. p x x A)((\lambda x. p x x A)(y I))) I \quad \frac{\beta}{\beta} \rightarrow$

$p((\lambda x. p x x A)((\lambda x. p x x A) I \quad \frac{\beta}{\beta} \rightarrow$

$p((\lambda x. p x x A)(p A A) I \quad \frac{\beta}{\beta} \rightarrow$

First reduction of 1 yields:

$$(\lambda x. p x x( y I))(p A A) I \quad \frac{\beta}{\beta} \rightarrow$$

$(\lambda y. p(p A A)(p A A)(y I)) I .$

This term is longer than the final result in the previous reduction. □
5. A RECURSIVE PERPETUAL STRATEGY

5.0. Introduction. In this section we will construct a recursive perpetual one step strategy $F_{\infty}$. As an application of $F_{\infty}$ we show that the contraction of a redex $(\lambda x.P)Q$ where $x \in \text{FV}(P)$ in a term with an infinite reduction sequence yields a similar term.

5.1. Definition. (i) Let $M \in \lambda$. Then the predicate $\infty$ is defined by
\[ \infty(M) \iff M \text{ has an infinite reduction sequence.} \]

(ii) Let $R = (\lambda x.P)Q$. If $x \in \text{FV}(P)$ we call $R$ an I-redex, otherwise $R$ is called a K-redex.

(iii) If $M$ is not in nf, the left-most redex of $M$ is the redex of which the head-\(\lambda\) is not preceded by the head-\(\lambda\) of any other redex.

5.2. Definition. Let the reduction strategy $F_{\infty}$ be defined as follows by induction on the length of the terms:

\[
F_{\infty}(M) = \begin{cases} 
\infty & \text{if } M \text{ is in nf.} \\
\text{Otherwise, let } M = C[(\lambda x.P)Q] \text{ where } R = (\lambda x.P)Q \text{ is the left-most redex of } M. \text{ Then:} \\
C[Q|x]P & \text{if } R \text{ is an I-redex.} \\
\text{Otherwise (if } R \text{ is a K-redex):} \\
C[P] & \text{if } Q \text{ is in nf.} \\
C[(\lambda x.P)(F_{\infty}(Q))] & \text{if } Q \text{ is not in nf.}
\end{cases}
\]

5.3. Definition. (i) Let $R$ be the redex $(\lambda x.P)Q$. The re of $R$ is $(\lambda x.P)$ and the dex of $R$ is $Q$.

(ii) Let $M$ be a term not in nf. The derived term of $M$, notation $M^+$, is the dex of the left-most redex in $M$.

(iii) Let $M$ be a term. Its derived sequence $M^0, M^1, \ldots, M^n$ is defined by $M^0 \equiv M$, $M^{k+1} \equiv (M^k)^+$, as long as $M^k$ is not in nf, otherwise $M^{k+1}$ is not defined. Clearly each derived sequence is finite.
(iv) $R^i$, the left-most redex of $M^i$, is called the special redex of order $i$ of $M$ ($0 \leq i < n$). See figure:

$$M^i \equiv M^0 \cup R^0 \equiv (\lambda x_0.P_0)^{M_1} \cup R^1 \equiv (\lambda x_1.P_1)^{M_2} \cup \ldots \cup R^{n-1} \equiv (\lambda x_{n-1}.P_{n-1})^{M_n}$$

where $M^n$ is in nf.

5.4. Remark. As can be seen from def. 5.2 and 5.3, $F_\infty$ contracts the first $I$-redex in the sequence $R^0$, $R^1$, ..., $R^{n-1}$ if there is such a redex, otherwise $F_\infty$ contracts $R^{n-1}$.

5.5. Lemma. Let $M \equiv C[(\lambda x.P)Q]$ where $R \equiv (\lambda x.P)Q$ is the left-most redex. Suppose that

(i) $R$ is a $K$-redex, (ii) $\infty(M)$ and (iii) not $\infty(Q)$.

Then $\infty(C[P])$.

Proof. Let $M \equiv M_0 \overset{\beta}{\rightarrow} M_1 \overset{\beta}{\rightarrow} M_2 \overset{\beta}{\rightarrow} \ldots$ be an infinite reduction sequence. There are two cases.

1. $(\lambda x.P)Q$ is never contracted in the reduction sequence. Then for all $i$, $M_i \equiv C_i[(\lambda x.P_i)Q_i]$ where $P_i \overset{\beta}{\rightarrow} P_{i-1}$, $Q_i \overset{\beta}{\rightarrow} Q_{i+1}$ and $C_i[\ ]$ are contexts (with one empty place) such that $C_i[z] \overset{\beta}{\rightarrow} C_{i+1}[z]$ ($z$ is a fresh variable). That the reductions of $M$ are separated in this way, follows because $(\lambda x.P)Q$ is left-most, hence nothing can be substituted in $P$ or $Q$. Moreover $(\lambda x.P_i)Q_i$ stays left-most in $M_i$ for the same reason.

Now because not $\infty(Q)$, there is an $m$ such that $Q_{m'} \equiv Q_m$ for all $m' > m$, i.e. for all $n$ in the reduction $M_{m+n} \overset{\beta}{\rightarrow} M_{m+n+1}$ is a redex outside $Q_{m+n}$ contracted. Hence for some $f \in \omega^\omega$ there is an infinite reduction sequence $\{C_f(i)[P_f(i)] | i \in \omega\}$ where $C_f(i)[P_f(i)] \overset{\beta}{\rightarrow} C_f(i+1)[P_f(i+1)]$.

2. In the reduction sequence $\{M_i\}$ the redex $(\lambda x.P)Q$ is contracted: by the same argument as in case 1. we have

$M_0 \overset{\beta}{\rightarrow} \ldots \overset{\beta}{\rightarrow} M_n \equiv C_n[(\lambda x.P_n)Q_n] \overset{\beta}{\rightarrow} M_{n+1} \equiv C_n[P_n] \overset{\beta}{\rightarrow} \ldots$ for some $n$.

Hence for some $g \in \omega^\omega$ there is an infinite reduction sequence $\{C_g(i)[P_g(i)] | i \in \omega\}$. \[\]
5.6. **Theorem.** \( F_{\infty} \) is a recursive perpetual one step strategy.

Proof. From def. 5.2 it is clear that \( F_{\infty} \) is a recursive one step strategy. Now we prove that \( F_{\infty} \) is perpetual. Let \( M = C[(\lambda x.P)Q] \) where \( R = (\lambda x.P)Q \) is the left-most redex. Let \( \infty(M) \) and let

\[
M \rightarrow M_0 \rightarrow M_1 \rightarrow M_2 \rightarrow \ldots
\]

be an infinite reduction sequence.

The proof that \( \infty(F_{\infty}(M)) \) uses induction on the length of \( M \) (in the case 2.2.2).

1. \( R \) is an I-redex.

1.1. There is an \( n \) such that in \( M_n \rightarrow M_{n+1} \) \( R_n \) is contracted, where \( R_n \subseteq M_n \) is the residual of \( R \). Because \( R \) is left-most it is evident that \( M_i = C_i[(\lambda x.P_i)Q_i] \) for \( i \leq n \) where \( R_i = (\lambda x.P_i)Q_i \) is the residual of \( R \) and \( R_i \) is left-most in \( M_i \). Moreover

\[
P_i \rightarrow P_{i+1}, \quad Q_i \rightarrow Q_{i+1} \quad \text{and} \quad C_i[z] \rightarrow C_{i+1}[z] \quad (i+1 < n).
\]

Now \( \infty(F_{\infty}(M)) \) because \( F_{\infty}(M) = C[Q[x] P] \overset{\beta}{\longrightarrow} C_n[Q_n[x] P_n] = M_{n+1} \).

1.2. Here for all \( i, \) \( M_i = C_i[(\lambda x.P_i)Q_i] \) where \( P_i \rightarrow P_{i+1}, \)

\[
Q_i \rightarrow Q_{i+1} \quad \text{and} \quad C_i[z] \rightarrow C_{i+1}[z].
\]

This gives the infinite reduction sequence \( \{C_i[(\lambda x.P_i)Q_i] \mid i \in \omega \} \). That this sequence is indeed infinite, follows because \( x \notin P_i \).

2. \( R \) is an K-redex.

2.1. \( Q \) is in nf. Then \( F_{\infty}(M) = C[P] \) and because not \( \infty(Q) \) we have by 5.5 \( \infty(C[P]) \).

2.2. \( Q \) is not in nf. Then \( F_{\infty}(M) = C[(\lambda x.P)(F_{\infty}(Q))] \).

\[
2.2.1. \text{Not } \infty(Q). \text{ By 5.5 } \infty(C[P]), \text{ hence } \infty(F_{\infty}(M)) \text{ because } F_{\infty}(M) = C[(\lambda x.P)(F_{\infty}(Q))] \rightarrow (C[P]).
\]

\[
2.2.2. \infty(Q). \text{ By induction hypothesis } \infty(F_{\infty}(Q)), \text{ hence } \infty(F_{\infty}(M)).
\]

5.7. **Remark.** The proof of 5.6 is non-constructive; however realizing the explicit action of \( F_{\infty} \) (see 5.4) a constructive proof of 5.6 can be given.

As an application of the perpetuity of \( F_{\infty} \) we will prove the following theorem.

5.8. **Theorem.** If \( M \rightarrow M' \) by contracting an I-redex in \( M \), then

\[
\infty(M) \Rightarrow \infty(M').
\]

As a corollary we obtain two known results of the \( \lambda I \)-calculus.
5.9. Corollary. In the \( \lambda I \)-calculus one has

(i) If \( M \) has a nf, then \( M \) strongly normalizes, i.e., each reduction sequence of \( M \) terminates.

(ii) If \( M \) has a nf, then all subterms of \( M \) have a nf.

Proof. (i) immediate by 5.8.

(ii) If \( M \) had a subterm without nf, then \( M \) would have an infinite reduction sequence and hence by (i) no nf. 

The proof of 5.8 for the \( \lambda K \)-calculus is more complicated than that of 5.9 for the \( \lambda I \)-calculus. The latter proof runs as follows:

Let \( M \equiv C\![\!(\lambda x. P)Q\!)\] and \( M' \equiv C\![\![Q|x]P\!]\). Let \( M \equiv M_0 \rightarrow M_1 \rightarrow \cdots \) be an infinite reduction sequence of \( M \). Underline in \( M \) as follows \( C\![\!(\lambda x. P)Q\!)\]. Then each term \( M_i \) in the sequence can be provided with lines which indicate the residuals of \( (\lambda x. P)Q \) in \( M_i \). By taking the complete developments of the resulting underlined sequence an infinite reduction sequence is obtained, which will be called the projection of the reduction sequence \( \{M_i\} \). The following example shows that this method of proof is false for the \( \lambda K \)-calculus:

Let \( \infty(\Omega) \), then

\[
\begin{align*}
\lambda x.(K\!x)\!\Omega &\quad \text{cpl} \\
K\!\Omega &\quad \text{cpl} (\lambda x.I)\!\Omega \\
&\quad \text{cpl} I \quad (\lambda x.I')\!\Omega' \\
&\quad \text{cpl} (\lambda x.I)'\!\Omega'' \\
&\quad \text{cpl} \quad (\lambda x.I)'\!\Omega''
\end{align*}
\]

Therefore the sequence 

\[
(\lambda x.K\!x)\!\Omega \rightarrow (\lambda x.I)\!\Omega \rightarrow (\lambda x.I')\!\Omega' \rightarrow \cdots \rightarrow (\lambda x.I)'\!\Omega''
\]

is said to be non-projectible.

We will prove 5.8 by observing that if 

\( \infty(M) \), then \( \Gamma^+_M(N) \) is an infinite reduction of \( M \), which is projectible and hence \( \infty(M') \). The proof occupies 5.10 - 5.16.

5.10. Definition. (i) \( M \in I\!\!\Lambda \) iff \( M \in \Lambda \), see 1.2, and only I-redices in \( M \) are underlined.

(ii) Let \( M \in \Lambda \). The special redices of \( M \) are defined analogously to 5.3.
5.11. **Definition.** The reduction relation \( \overset{\beta}{\rightarrow} \) contracts only underlined redices. Another reduction relation \( \overset{\beta}{\rightarrow} \) for terms in \( \lambda \beta \) is defined as follows:

\[
C \left[ (\lambda x. P) Q \right] \overset{\beta}{\rightarrow} C \left[ [Q|x] P \right]
\]

where \( C[\_\_] \) is a context with one hole.

5.12. **Lemma.** A special redex \( R \) of \( M \) (being underlined or not) is not part of the re of any redex in \( M \).

**Proof.** Induction on the order \( i \) of \( R \).

\( i = 0 \). Then \( R \) is the left-most redex of \( M \). If \( R \) would be in the re of some redex of \( M \), then \( R \) would not be the left-most redex of \( M \).

\( i+1 \). Then \( R \) is the special redex of order \( i \) of \( M^* \). By the induction hypothesis, \( R \) is not part of the re in a redex in \( M^* \). Hence if \( R \) were part of some re in \( M \), then also \( M^* \) is part of this re. But then \( R^0 \) (see 5.3) would not be the left-most redex in \( M \).

5.13. **Lemma.** Let \( M, N \in \lambda \beta \). If (i) \( M \overset{\beta}{\rightarrow} N \) or (ii) \( M \overset{\beta}{\rightarrow} N \) by contracting a special redex, then \( M \in I \lambda \beta \Rightarrow N \in I \lambda \beta \).

**Proof.** An underlined I-redex \( (\lambda x. P) Q \) can degenerate to a K-redex only if \((\_\_\_\_)\) inside \( P \) all free occurrences of \( x \) are erased.

In case (i) \((\_\_\_\_)\) cannot happen since the contracted redex is an I-redex.

In case (ii) \((\_\_\_\_)\) cannot happen since no special redex is part of \( P \), by 5.11.

5.14. **Lemma.** Let \( M, N \in \lambda \) and let \( M \overset{\beta}{\rightarrow} M' \) by contraction of a special redex. Let \( (M, u) \in I \lambda \beta \). Then there exists a \( (M', u') \in I \lambda \beta \) such that \( (M, u) \overset{\beta u-\beta}{\rightarrow} (M', u') \), where \( \overset{\beta}{\rightarrow} \) is \( \overset{\beta}{\rightarrow} \) or \( \overset{\beta}{\rightarrow} \).

\[
(M, u) \in I \lambda \beta \\
\beta u-\beta \\
M \quad (M', u') \in I \lambda \beta \\
\text{special } \beta \\
M'
\]

**Proof.** The underlining \( u' \) for \( M' \) follows from that of \( M \) by making the contraction in \( (M, u) \) homologous to that in \( M \). That \( (M', u') \in I \lambda \beta \) follows by 5.3.
5.15. Lemma. Let $M, N \in \Lambda$, then

Moreover if $M \in \Lambda$, then $M \xrightarrow{\beta} N$ in the diagram.

Proof. Let $(\lambda x.P)Q$ be the redex contracted in $M \xrightarrow{\beta} N$. Underline this redex as follows: $(\lambda x.P)Q$.

$M \xrightarrow{\beta} N$ is then the complete reduction of $M$ as $\lambda\beta$-term and hence $M \xrightarrow{\text{cpl}} N'$ is a complete reduction of $M$ as $\lambda\beta$-underlined term. By FD' 1.12, it follows that $M' \xrightarrow{\beta} N'$ which is in fact a complete reduction w.r.t. the underlining $\lambda\beta$.

Now suppose $M \in \Lambda$. Then by 5.13(i) each term in the $\lambda\beta$-complete reduction of $M$ is an $\lambda\beta$-term. Hence each of these terms contains a $\lambda\beta$-redex. Therefore $M' \xrightarrow{\beta} N'$.

5.16. Proof of 5.2.

Suppose $\infty(M)$ and $M \equiv C[(\lambda x.P)Q] \xrightarrow{\beta} M' \equiv C[[Q|x]P]$ is the contraction of an $I$-redex. We have to show $\infty(M')$. Let $M_n \equiv F_0^\infty(M)$. By the perpetuity of $F_\infty$, $M \equiv M_0 \xrightarrow{\beta} M_1 \xrightarrow{\beta} \ldots$ By 5.4, $M_1 \xrightarrow{\beta} M_{i+1}$ is the result of contracting a special redex.

Let $(M_i, \nu_i)$ be $C[(\lambda x.P)Q] \in \Lambda$. By 5.14 there are $\nu_i$ such that $M_i \equiv (M_i, \nu_i) \in \Lambda$ and $(M_i, \nu_i) \xrightarrow{\beta \nu_i} (M_{i+1}, \nu_{i+1})$.

Let $M'_i$ be the result of a complete reduction of $(M_i, \nu_i)$.

If $(M_i, \nu_i) \xrightarrow{\beta} (M_{i+1}, \nu_{i+1})$ then by 5.1.5 $M_i \xrightarrow{\beta \nu_i} M_{i+1}$.

If $(M_i, \nu_i) \xrightarrow{\beta} (M_{i+1}, \nu_{i+1})$ then by 1.14 $M_i \equiv M_{i+1}$.

Hence we have
By FD a sequence of consecutive $\frac{\alpha}{\beta} \Rightarrow$ is always finite. Therefore a subsequence of the $M_1'$ is an infinite reduction for $M'$, i.e., $\infty(M')$.

5.17. Remark. Note that by 1.18 in the figure in the proof of 5.15 one has $M_1 \frac{\alpha}{\beta} \Rightarrow M_1'$. This observation is the essence of the proof of the Church-Rosser theorem in [4].

5.18. Remark. A perpetual strategy $F$ cannot depend only on the skeleton of a term.
Proof. Let $M = (\lambda x.(\lambda a.aa))(\lambda y.(\lambda p.q.q)(\lambda z.vv))$ and $M' = (\lambda x.v(\lambda a.aa))(\lambda y.(\lambda p.q.p)(\lambda z.z)).$
Both terms have the same skeleton and only two redices (the underlined ones). To obtain an infinite reduction sequence $F$ must contract in $M$ the first and in $M'$ the second redex.
6. \( \beta \) - VERSUS \( \beta \gamma \) - REDUCTION.

In [5] p.124 it is proved that: \( M \) has a \( \beta \gamma \)-normal form \( \iff \) \( M \) has a \( \beta \)-normal form. The implication \( \iff \) is trivial, but \( \implies \) gives some problems. The authors remark that while it seems as if the proof should be trivial, they did not know a shorter proof than the one they give there.

The proof that we present here is more straightforward and has the advantage of proving something more: viz. the theorem of Postponement of \( \gamma \)-reductions [4] p.132, Thm.2. This is useful because the proof presented there contains an error, as noted by Nederpelt in [8] p.65. He also gives a proof of this theorem of which we will give a brief sketch. There is a simple connection between his proof and ours.

6.1. **Notation.** Let \( M \) be a \( \lambda \)-term. Then \((M)_0 = M, (M)_{n+1} = \lambda x. (M)_n x\) where \( x \notin \text{FV}(M)_n \).

6.2. **Remark.** The \( M_n \) are \( \gamma \)-expansions of \( M \) and one easily verifies:

(i) \((M)_n)^m = (M)_{n+m}\)

(ii) \( (M)_n \xrightarrow{\beta} (M)_1 \)

(iii) \( (M)_n N \xrightarrow{\beta} MN \)

6.3. **Definition.** A labeling \( L \) of a \( \lambda \)-term \( M \) is a map which assigns a natural number to each occurrence of a subterm of \( M \).

Remark: the labelings in this paragraph have nothing to do with those in §1,2 and 3.

6.4. **Notation.** (i) If \( M \) is labeled by \( L \) we write \( M^L \). Also we write the labels as superscripts; example: \( M^L = (x^1(y.y.y)^0)^2) \).

Sometimes a self-explaining notation like \( (M^L)^L' \) is used.

(ii) \( M^L \xrightarrow{\phi} M \) means that \( M \) is the result of omitting the labels in \( M^L \).

6.5. **Definition.** Let \( \phi \) be the mapping which changes superscripts into subscripts. By our notation \( \phi \) maps labeled \( \lambda \)-terms to \( \lambda \)-terms.
Example. Let $M^L$ be as in 6.4. Then $\psi(M^L) = M_L = x_1(\lambda y.(y_2y_0)_2 = (\lambda f.xf)(\lambda e.(\lambda d.(\lambda y.(\lambda c.(\lambda b.(\lambda a.\lambda b)y)c))d)e)$

6.6. Notation. In stead of $A = \psi(B^L)$ we will write $B^L \rightarrow_{\omega} A$.

6.7. Lemma. (i) $A \not\rightarrow_{\omega} B^L \Rightarrow A \not\rightarrow_{\beta} B$

(ii) $((\lambda x. P^P)\rho Q^Q)_s \rightarrow_{\beta} [Q^Q,x] P^P + S$

Proof of (i) is evident.

(ii) $((\lambda x. P^P)\rho Q^Q)_s \rightarrow_{\beta} ((\lambda x. P^P)\rho Q^Q)_s \rightarrow_{\beta} [Q^Q,x] P^P + S$.

6.8. Definition of labeled $\beta$-reduction $\rightarrow_{lab,\beta}$:

(i) $((\lambda x. P^P)\rho Q^Q)\beta \rightarrow_{lab,\beta} [Q^Q,x] P^P + S$

(ii) If $M^L \rightarrow_{lab,\beta} N^L$ then $C[M^L] \rightarrow_{lab,\beta} C[N^L]$ for every labeled context with one empty place. Here $[|]$ is the usual substitution operator, plus the extra rule: $[Q^Q,x] x^n = Q^{Q+n}$.

6.9. Lemma. i.e. if $A \not\rightarrow B$ and $L$ is a labeling of $A$, then there is a labeling $L'$ of $B$ such that $A \rightarrow_{lab,\beta} B^L$.

Proof. Clear.

6.10. Lemma. i.e. $B^L \rightarrow_{lab,\beta} C^L \Rightarrow \psi(B^L) \rightarrow_{\beta} \psi(C^L)$

Proof. Immediate from 6.5, 6.8 and 6.7(ii).
6.11. Main lemma.

\[ A \xrightarrow{\varphi} B \]
\[ \beta \]
\[ \lambda b, \beta \]
\[ D \xrightarrow{\varphi} C' \]

Proof. Immediate from 6.10. ✗

As a first corollary we prove: if \( M \) has a \( \beta\eta \)-normal form, then \( M \) has a \( \beta \)-normal form. We need two lemma's to do this:

6.12. Lemma. \( M \) is a \( \beta\)-nf. \( \implies \ \varphi(M^L) \) has a \( \beta \)-nf. (for all \( L \)).

Proof. The class \( \text{BNF} \) of \( \beta \)-nf's can be inductively defined by:

i) \( x \in \text{BNF} \)

ii) \( \lambda M \in \text{BNF} \implies xM \in \text{BNF} \)

iii) \( \lambda x. M \in \text{BNF} \)

Now we apply induction on this definition.

Case i): \( M = x \), \( \varphi(x^N) = (x)_n \xrightarrow{\beta} (x)_1 = \lambda y. xy \) by 6.2(ii), hence \( \varphi(x^N) \) has a \( \beta \)-nf.

Case ii): for simplicity suppose \( M = xA \). Then \( \varphi(M^L) = \varphi((xA)^L) = \varphi(((xA^L)_1 A^L_2)^L) = ((xA^L_1)_1 A^L_2 A^L_3) \). By 6.2(iii), \( \varphi(M^N) \xrightarrow{\beta} (xA^L_1 B^L_2)^L \), the last reduction if \( l_3 > 0 \).

By induction hypothesis \( A^L_1, B^L_2 \) have a \( \beta \)-nf, hence \( xA^L_1 B^L_2 \) also.

Case iii): \( M = \lambda x. N \). \( \varphi(M^N) = \varphi((\lambda x. N^L)^L) = (\lambda x. N^L)_1 \xrightarrow{\beta} (\lambda x. N^L)_2 \xrightarrow{\beta} \lambda y. [y|x] N^L \), \( \lambda x. N^L \)

By induction hypothesis \( N^L \) has a \( \beta \)-nf, hence also \( \lambda x. N^L \) and \( \varphi(N^L) \). ✗

6.13. Lemma. If \( P \rightarrow_{\eta} Q \) and \( Q \) has a \( \beta \)-nf, then \( P \) has a \( \beta \)-nf.

Proof. (See diagram) Let \( Q \xrightarrow{\beta} R \). Let the \( \eta \)-redex contracted in \( P \rightarrow_{\eta} Q \) be \( \lambda x. Mx \). Then we label \( Q \) by giving the resulting \( M \) label 1 and every other subterm (occurrence) label 0. This is \( Q^L \). Evidently
\( Q \stackrel{L}{\rightarrow} P \). By 6.9 an \( R' \) such that \( Q \stackrel{L}{\rightarrow} \) lab.\( \beta \) \( \Rightarrow R' \Rightarrow R \) can be found.

By the main lemma we have \( P \rightarrow \beta \Rightarrow (RL') = S \) and by 6.7(i) \( S \Rightarrow R \).

Suppose moreover that \( R \) is the \( \beta \)-nf. of \( Q \). Then by 6.12 \( S \) has a \( \beta \)-nf., hence \( P \) has a \( \beta \)-nf. \( \square \)

6.14. Corollary. \( M \) has a \( \beta \)-nf. \( \iff \) \( M \) has a \( \beta \gamma \)-nf.

Proof. (\( \Longleftarrow \)) Induction on the numbers of steps necessary to reduce \( M \) to \( \beta \gamma \)-nf., using 6.13. \( \square \)

(\( \Longrightarrow \)) Trivial, since \( \gamma \)-contractions of a \( \beta \)-nf. do not create new \( \beta \)-reduces. \( \square \)

6.15. Corollary. (Postponement of \( \gamma \)-reductions)

\( \Rightarrow \)

Proof. In the first part of the proof of 6.13 we proved

\[ P \xrightarrow{\gamma} Q \text{ from which } P \xrightarrow{\gamma} Q \text{ directly follows.} \]

The rest of the proof is routine. \( \square \)

Nederpelt defines a new reduction \( \kappa \rightarrow \) as follows:

I. \[ A \quad \kappa \rightarrow A \]

II. \[ \frac{A \quad \kappa \rightarrow B}{\lambda x. Ax \quad \kappa \rightarrow B} \quad (x \notin \text{FV}(A)) \]

III. \[ \frac{A \quad \kappa \rightarrow B \quad C \quad \kappa \rightarrow D}{AC \quad \kappa \rightarrow BD} \]

IV. \[ \frac{A \quad \kappa \rightarrow B}{\lambda x. A \quad \kappa \rightarrow \lambda x. B} \]

\( \kappa \rightarrow \) has the following properties:

i) \[ A \quad \kappa \rightarrow B \quad \Rightarrow \quad A \quad \eta \rightarrow B \]

ii) \[ A \quad \eta \rightarrow B \quad \Rightarrow \quad A \quad \kappa \rightarrow B \]

iii) \[ A \quad \kappa \rightarrow B \]

\[ \beta \ast \quad \beta \]

\[ D \quad \kappa \rightarrow \quad C \]

This gives directly \[ \kappa \rightarrow \], which gives \[ \eta \rightarrow \]

from which the theorem of Postponement of \( \eta \)-reductions follows.

Remark that \( \kappa \rightarrow \) is not transitive; example:

\[ \lambda x. A(\lambda y. xy) \quad \kappa \rightarrow \lambda x. Ax \quad \kappa \rightarrow A \quad \text{but not} \]

\[ \lambda x. A(\lambda y. xy) \quad \kappa \rightarrow \quad A. \]

Now there is a simple connection between Nederpelt's and our method:

\[ A \quad \kappa \rightarrow B \quad \Leftrightarrow \quad A \quad \varphi \rightarrow B^L \quad \text{for some} \quad L. \]

Properties i) - iii) about \( \kappa \rightarrow \) follow from properties of \( \varphi \rightarrow \).
7. NON-NORMALIZING S-TERMS

An S-term is an applicative combination of S's.
At the Rome conference on λ-calculus (March 1975) the question was raised whether there are S-terms without a normal form (nf).
Several people, including ourselves, provided independently solutions. We will treat three examples. In each case the proof that the term has no nf is rather different.
The interest in the examples is that they provide terms with a rather unusual reduction pattern.

The length of an S-term is the number of its S's. If \( a_n \) is the number of S-terms with length n, then by the formula of Catalan (cf. [3] p. 64)

\[
a_n = \frac{1}{2n-1} \binom{2n-1}{n}.
\]

The first values of \( a_n \) are indicated in fig. 1.
Let \( b_n \) be the number of S-terms of length n without a nf.
Mr. Duboué has calculated by computer upper bounds for \( b_n \), for \( n < 10 \), see fig. 1.

\[
\begin{array}{cccccccccc}
 n & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 \\
 a_n & 1 & 2 & 5 & 14 & 42 & 132 & 429 & 1430 & 4862 \\
 b_n & 0 & 0 & 0 & 0 & 0 & 2 & \lessapprox 39 & \lessapprox 231 \\
\end{array}
\]

(fig. 1)
The bounds are not exact, since the computer only reduced a term a (large) finite number of times in order to conclude that it might be non-normal. For \( n = 7 \), theorem 6.4 proves that the bound is exact.

7.1. Notations. \( C[\ ] \) is a context containing one or more holes.
\( F^0X = X; F^{n+1} = F(F^nX) \).
\( M \rightarrow N \iff CLM \rightarrow C[N] \) for some context \( C[\ ] \), and \( M \neq C[N] \).

7.2. Lemma. If \( M \) is an S-term having an infinite \( \rightarrow \) reduction path, then \( M \) has no nf (in combinatory logic, nor its translation \( M_\lambda \) in the \( \lambda \)-calculus).

Proof. Since S-terms are \( \lambda I \)-terms this is a well-known property, cf. 5.9.(i).
7.3. **Theorem.** (Petorossi) Let \( A = SSS \), \( \omega = SAA \), \( M = \omega \omega \). Then \( M \) has no nf.

**Proof.** Note that \( A^x y \rightarrow xy \), hence by induction \( A^n x y \rightarrow xy \).

Claim: \( A^n \omega(A^n \omega) \rightarrow A^{n+1} \omega(A^{n+1} \omega) \).

Indeed, \( A^n \omega(A^n \omega) \rightarrow \omega(A^n \omega) = SAA(A^n \omega) \rightarrow A^{n+1} \omega(A^{n+1} \omega) \).

By the claim \( M \) has an infinite \( \rightarrow \) path, hence no nf.

7.4. **Theorem.** The shortest S-term without nf is of length 7.

In fact there are exactly two such terms: \( X_1 = S(SS)SSSS \) and \( X_2 = SSS(SS)SS \).

**Proof.** (A different proof has been given by Monique Baron.)

Mr. Duboué has shown by computer that all S-terms of length \( \leq 6 \) are normalizable, as well as all other S-terms of length 7.

Now we will prove that \( X_{1,2} \) have no nf.

Let \( B = S(SS) \), \( C = S(BS)S \) and \( Y = BC \).

Then \( Bxy \rightarrow S(xy)(y(xy)) \), \( Bxyz \rightarrow y(xy)z \),

\( Cx \rightarrow x(Sx)(Sx) \), and

\( 1 \) \( Yx \rightarrow x(Sx)(Sx) \).

Now

\( 2 \) \( X_1 \rightarrow X_2 \rightarrow BSSC \rightarrow BBC \rightarrow C(BC) \rightarrow Y(SY)(SY) \).

**Def.** \( \mathcal{A} \) is the set of S-terms inductively defined by

\( SY \in \mathcal{A} \)

\( M \in \mathcal{A} \implies SM \in \mathcal{A} \)

\( M, N \in \mathcal{A} \implies MN \in \mathcal{A} \)

\( 3 \) **Lemma.** For all \( M \in \mathcal{A} \): \( Mxy \rightarrow Y C^M_{x,y} C_1^M \), where \( C_1^M, C_2^M \) are contexts such that (after reduction)

\( C^M_{1,2}[P,Q] \in \mathcal{A} \) for all \( P, Q \in \mathcal{A} \).

**Proof.** Induction on the structure of \( M \) (\( \in \mathcal{A} \)).

\( M \equiv SY \)

\( M \equiv SN \)

\( M \equiv PQ \)
(4) Cor. \( \forall M_1, M_2 \in \mathcal{A} \exists M_1', M_2' \quad Y M_1 M_2 \rightarrow Y M_1' M_2' \).

Proof. Let \( M_1, M_2 \in \mathcal{A} \). Then by (1) and (3)

\[
Y M_1 M_2 \rightarrow Y M_1 (SM_1)(SM_1) \rightarrow Y C_1 \left[ SM_1, SM_1 \right] C_2 \left[ SM_1, SM_1 \right] = Y M_1' M_2'. \quad \Box
\]

Now it follows by (2) and (4) that \( X_{1,2} \) have an infinite \( \rightarrow \) path. Therefore by 7.2 \( X_{1,2} \) have no nf. \( \Box \)

Now we present a third method of proving that an S-term has no nf.

7.5. Theorem. Let \( A = SSS \). Then AAA has no nf.

Proof. (den Hartog)

1. Def. Let \( SA \) be the calculus with terms built up by application from constants \( S, A \).

2. Fact. Each \( SA \)-term \( M \) is of the form \( SM_1 \ldots M_n \) or \( AM_1 \ldots M_n \).

The \( M_i \) are called the \( i \)-th component of \( M \).

3. Def. Reduction in \( SA \) is defined by

\[
\begin{align*}
A M & \rightarrow SSSM \\
SPQ M & \rightarrow PR(QR)M
\end{align*}
\]

4. Lemma. Let \( M \) be a subterm of an \( SA \)-reduct \( M' \) of \( AAA \). Then the components of \( M \) all end with the letter \( A \) except possibly the 1st and 2nd components, in which case they are \( S \).

Proof. By induction on the \( SA \)-reduction sequence \( AAA \rightarrow M' \). \( \Box \)

5. Def. If \( M \rightarrow N \) is an one step \( SA \)-reduction, then \( M \) is a predecessor of \( N \).

6. Theorem. AAA has in \( SA \) an infinite reduction path.

Proof. The \( SA \)-reduction of \( AAA \) only can terminate in a term of the form \( S, SP \) or \( SPQ \).

Clearly \( S \) and \( SP \) have no predecessors. The only possible predecessor of \( SPQ \) is \( SSYP \). The only possible predecessor of \( SSYP \) is \( SSXSP \).

But this term does not satisfy the condition of lemma 4. \( \Box \)

7. Cor. The S-term AAA has no nf.

Proof. Since AAA has an infinite reduction chain, so has AAA. \( \Box \)
7.6. **Fact.** Let \( A = SSS \), \( B = S(SS) \). Then the following terms have no \( \text{n.f.} \):
- \( SAA(SAA) \)
- \( BSSSS \)
- \( AAA \)
- \( SAAA \)
- \( SBBB \)
- \( AA(SS) \).

The first three were treated above. Proofs of the non-normalization of the other terms were given by Hindley and Gerd and Aleid Mitschke. Other examples were provided by Duboué, and Börger and Carstens.

7.7. **Question.** 1. Is convertibility between \( S \)-terms decidable?
   2. Is the set of \( S \)-terms having a \( \text{n.f.} \) decidable?

7.8. **Exercise.** Prove that \( S(SS)(SS)(SS)SS \) has a \( \text{n.f.} \).
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Introduction. Let $\mathcal{M} = \langle M, \cdot \rangle$ be a $\lambda$-algebra (i.e. a model of the $\lambda$-calculus). Elements of $M$ are thought of as functions. Arbitrary $f: M \to M$ are called external functions. Such a function is representable (by an element $a \in M$) if $\forall b \in M \ f(b) = a \cdot b$. $f$ is definable in $\mathcal{M}$ if $f$ is representable by $[F]^{\mathcal{M}}$ for some closed term $F$.

Here $[F]^{\mathcal{M}}$ denotes the value of $F$ in the model $\mathcal{M}$.

Other notations:

- $x, y, \ldots$ denote variables of the $\lambda$-calculus.
- $a, b, \ldots$ denote variables ranging over the elements of a $\lambda$-algebra.
- $F, G, \ldots$ denote $\lambda$-terms.
- The numerals $0, 1, 2, \ldots$ denote some adequate representation of the natural numbers as $\lambda$-terms e.g. those of Church: $\mathbb{N} = \lambda f x. \ f^\mathbb{N}(x)$.

If $T$ is a consistent extension of the $\lambda$-calculus, $\mathcal{M}^{(eq)}(T)$ is the closed term-model of $T$, i.e. all (closed) $\lambda$-terms modulo provable equality in $T$.

A $\lambda$-algebra $\mathcal{M}$ is hard if its domain consists exactly of the images of closed terms. In such an $\mathcal{M}$ a function is representable iff it is definable.

For other terminology see Barendregt [1976].
The three sections of the paper treat different aspects of the notion of representability.

In §1 attention is restricted to the standard extensional term model $\mathcal{M} = \mathcal{M}(\lambda \eta)$.

Church's $\delta$ is an external function satisfying

\begin{equation}
\delta MM = 0 \text{ if } M \text{ is in normal form (nf)}
\end{equation}

\begin{equation}
\delta MM' = 1 \text{ if } M, M' \text{ are different nf's.}
\end{equation}

In Böhm [1972] it is proved that $\forall N_1 \ldots N_n \text{ different } \beta \eta \text{ nf's}$

$\exists F \vdash FN_1 = i$. As a consequence it follows that for every finite set of nf's there is a term $\delta$ satisfying (*).

At the Orléans logic conference (1972) the question was raised whether the general Church's $\delta$ is definable as a $\lambda$-term.

We will give a negative answer which was already established in Barendregt [1972] and independently in Wadsworth [1972] (see also Hindley and Mitschke [1975]). All three proofs of the non-existence of $\delta$ are different.

Furthermore it is proved that the only definable functions from the terms into the numerals are the constant functions.

In §2 it will be proved that definable functions in various $\lambda$-algebras have a range of cardinality 1 or $\aleph_0$. For representable functions this is not true in $D_\infty$ and $P_\omega$.

Two external functions $f$ and $g$ on $\mathcal{M}$ are dual, notation $f \equiv \mathcal{M} g$, if $f(a).b = g(b).a$ for all $a, b \in \mathcal{M}$.

A model $\mathcal{M}$ is rich if for all $f, g$:

$f \equiv \mathcal{M} g \implies f$ and $g$ are representable in $\mathcal{M}$.

The results of §3 are: $D_\infty$ and $\mathcal{M}(\lambda \eta)$ are rich; rich models are extensional; hard sensible models (e.g. the interior of $D_\infty$) are not rich.

We would like to draw the proof of 3.6 to the readers attention. There variables of the $\lambda$-calculus are not just used in the usual way, but also serve as separate entities.
§1. Non definability results.

The main tool in this section is the "Bohm out" technique 1.4. This result is also of use in §2.

1.1 Def. Let BT(M) be the Böhm tree of M, see Barendregt [1976], §5. x ∈ BT(M) iff x ∈ FV(M) and occurs as a head variable in some label at a node of BT(M).

1.2 Def. (i) A selector is a term of the form U = x_1·...·x_n. A permutator is a term of the form C = λ x_1···x_n·x_{π(1)}···x_{π(n)} for some permutation π.

(ii) Simple terms are inductively defined by: Any variable, selector or permutator is a simple term. If P, Q are simple terms, so is PQ.

1.3 Lemma. Simple terms have a normal form (nf).

Proof. Realizing that each simple term is of the form x\vec{P}, U\vec{P}, C\vec{P} with \vec{P} simple U a selector and C a permutator, it can be shown by induction on the term length that they have a nf. □

1.4 Theorem. Let FV(M) = {x} and x ∈ BT(M). Then

(i) For some \vec{P}, \vec{Q}, with x ∈ FV(\vec{P}), λ \mapsto M\vec{P} = x\vec{Q} ("x is Böhmed out").

(ii) Moreover \vec{P} can be chosen as a sequence of simple terms.

Proof. Let x occur in BT(M) at depth k > 0. By a similar construction as in Barendregt [1976] 6.14, 6.15 for some Böhm-transformation T, x occurs in BT(M^T) at depth k-1. Iterating this leads to M^T = λ \vec{y}·x\vec{Q}, hence M^T\vec{y} = x\vec{Q}.

Checking the details of the construction of \vec{y} one verifies that M^T\vec{y} = M·...·x_i·...[x_j/Cx_j]·...[x_k/Ux_k]·...\vec{y} = M\vec{P} for some simple terms \vec{P} with x \not∈ FV(\vec{P}) (where C is a permutator and U a selector). □
1.5 Lemma. If F is not constant, i.e. \( Fx \neq FX \) for some \( X_1, X_2 \), and for some \( M, FM \) has a nf., then \( x \in \text{BT}(Fx) \) for all \( x \).

Proof. Note that if \( P, P' \) have equal finite \( \Omega \)-free Böhm-trees, then \( \lambda \vdash P = P' \). Now suppose \( x \notin \text{BT}(Fx) \) for some \( x \notin \text{FV}(M) \). Then \( \text{BT}(Fx) = \text{BT}(FM) \). But since \( FM \) is in nf, \( \text{BT}(FM) \) is finite and \( \Omega \)-free and hence \( \vdash Fx = FM \), i.e. \( F \) is constant. This contradiction shows \( x \notin \text{FV}(M) \implies x \in \text{BT}(Fx) \). But then by substitution \( x \in \text{BT}(Fx) \) for all \( x \).

1.6 Def. \( 0 = 1, n + 1 = K n \).

1.7 Lemma. The function \( \text{sg} \) is not \( \lambda \)-definable with respect to \( \{n|n \in \omega, \} \), i.e. for no \( \lambda \)-term \( F \vdash F 0 = 0, \vdash F n+1 = 1 \).

Proof. Suppose \( F \) exists. Then by 1.5 \( x \in \text{BT}(Fx) \). Hence by 1.4 \( FxP = xQ \) for some \( P, Q = Q_1 \ldots Q_m \). But then for all \( n > m, \vdash 1P = F n P = n Q_1 \ldots Q_m = n-m \) contradicting the Church-Rosser theorem since the \( k \) are different nf's.

1.8 Def. A system of terms \( \{M_n|n \in \omega\} \) is an adequate system of numerals iff

(i) Each \( M_n \) has a nf.

(ii) Each recursive function can be \( \lambda \)-defined with respect to the \( M_n \).

In Barendregt [1972] is shown that the second condition can be replaced by (ii'): The successor, predecessor and \( \text{sg} \) functions can be \( \lambda \)-defined with respect to the \( M_n \).

The following corollary was proved independently by Barendregt [1972] and Wadsworth [1972].

1.9 Cor. (Barendregt). (i) \( \{n|n \in \omega\} \) is not an adequate system of numerals. (ii) Church's \( \delta \) is not \( \lambda \)-definable.

Proof. (i) Immediate. (ii) If \( \delta \) were \( \lambda \)-definable, then so would be \( F \) in 1.7 since \( F = \lambda x. \delta x 0 0 1 \).
1.10 Let $w = \{n| n \in \omega\}$ be an adequate system of numerals and let $f$ be a map into $\omega$ definable by $F$. Then $f$ is constant.

Proof. First assume $w$ is Church's system of numerals, i.e. $n = \lambda f x . f^n(x)$ (or $\lambda f x . f \ldots (f x)$). Suppose $F$ is not constant, then by $1.5$ $x \in BT(Fx)$. Hence for some simple $P$ and $Q$, $\lambda t . FxP = xQ$.

Hence $\lambda t . FMP = MQ$ for all $M$. But $MQ$ can take arbitrary values and not $FMP$, since $\underline{n} \rightarrow P^n(P_1)P_3\ldots P_k$ is always in $\text{nf}$ by $1.3$.

Now let $\omega$ be an arbitrary system of numerals. It is well known how to define a term $G$ such that $Gn = n$.

Suppose a non constant $f : \text{terms} \rightarrow \omega$ would be definable, then $G \circ f$ were a definable non constant mapping into $\omega$. \(\square\)

First alternative proof (due to the referee).

Suppose $F$ is not constant, i.e. let $n_1 \neq n_2 \in \text{Ra}(F)$. Define $G$ as the $\lambda$-defining term of the recursive function $g(x) = 0$ if $x = n_1$, and $g(x) = 1$ else. Then the range of $G \circ F$ is $\{0, 1\}$ contrary to $2.3$.

Second alternative proof. By Barendregts lemma in de Boer [1975] it follows that if $\Omega$ is unsolvable and $N$ a $\text{nf}$, then

$$F \Omega = N \implies Fx = N \text{ for all } x.$$

(General genericity lemma) Now if the values of $F$ are numerals it follows that $F \Omega$ has a $\text{nf}$, i.e. $F$ is constant. \(\square\)

1.11 Cor. There is no $F$ such that

$$FM = \begin{cases} 0 & \text{if } M \text{ is a numeral (i.e. } \vdash M = \underline{n} \text{ for some } n) \\ 1 & \text{else} \end{cases}$$

for any adequate system.

1.12 Question: Is there a term $F$ such that

$$FM \text{ has a } \text{nf} \text{ (is solvable) if } M \text{ is a numeral}$$

$$\text{has no } \text{nf} \text{ (is unsolvable) else}.$$
2. The range property

2.1 Def. Let \( \mathcal{H} = < M, \cdot > \) be a \( \lambda \)-algebra. For each \( f \in M \), we define \( \text{Ra}^{\mathcal{H}}(f) \), the range of \( f \) in \( \mathcal{H} \), as follows:

\[
\text{Ra}^{\mathcal{H}}(f) = \{ f \cdot x | x \in M \}.
\]

Notation. \( \text{Ra}^{\mathcal{H}}(F) = \text{Ra}^{\mathcal{H}}([[F]]) \) for terms \( F \).

When possible, the superscript \( \mathcal{H} \) will be dropped in \( \text{Ra}^{\mathcal{H}} \).

2.2 Def. A \( \lambda \)-algebra \( \mathcal{H} \) satisfies the range property if for all \( f \in M \), the cardinality of \( \text{Ra}^{\mathcal{H}}(f) \) is 1 or \( \infty \).

2.3 Range theorem: (Barendregt; Myhill). Let \( T \) be a r.e. \( \lambda \)-theory. Then \( \mathcal{H}(T) \) (and also \( \mathcal{H}^0(T) \)) has the range property.

Proof. Suppose \( f \in M \) and \( \text{Ra}(f) = \{ m_0, \ldots, m_k \} \), \( k > 0 \). Define

\[
N_i = \{ x | f \cdot x = m_i \} \subseteq M. \]

Every such \( N_i \) is r.e. Therefore

\[
N = \bigcup_{i=1}^{k} N_i,
\]

the complement of \( N_0 \) is also r.e. Hence \( N_0 \) is recursive.

On the other hand \( N_0 \) is non-trivial and closed under equality, which contradicts Scott’s theorem, (Barendregt [1976] 2.21).

The proof for \( \mathcal{H}^0(T) \) is the same. \( \Box \)

2.4 Cor. \( \mathcal{H}^0(\lambda(\eta)) \) has the range property.

The range property, however, is not satisfied in every \( \lambda \)-algebra.

2.5 Theorem. \( \text{P}_\omega \) and \( \text{D}_\infty \) do not satisfy the range property.

Proof. Since the proof is similar in both cases, let \( S = (S, \ll) \) denote either \( (\text{P}_\omega, \subseteq) \) or \( (\text{D}_\infty, \subseteq) \). We define the following function

\[
f : S \rightarrow S \text{ by } f(x) = T \text{ if } x \neq \bot \text{ else } \bot \text{ (\( T \) and \( \bot \) are the largest respectively smallest element of \( S \)).}
\]
Claim $f$ is continuous. Then by Scott [1972], [1975] $f$ is representable and since $f$ has range of cardinality two we are done.

For open $0$ in $S$ one has: $x \in 0$ and $x \nleq y \Rightarrow y \in 0$.


Hence for open $0$, $\bot \in 0 \Rightarrow 0 = S$, and $0 \neq \emptyset \Rightarrow T \in 0$.

Now for every open set $0$, $f^{-1}(0)$ is open:

Case 1. $\bot \in 0$. Then $0 = S$ so $f^{-1}(S) = S$ which is open.

Case 2. $\bot \notin 0$. If $0 = \emptyset$, then we are done. Else $T \in 0$ and hence $f^{-1}(0) = S - \{\bot\} = \{x | x \neq \bot\}$

$U_{\bot}$ is open in $D_\infty$, see e.g. Barendregt [1976] 4.2.

$U_{\bot}$ is open in $P\omega$: Let $O_k = \{x | e_k \subseteq x\}$. Note $e_0 = \emptyset = \bot$ and that the $O_k$ form a base for the topology on $P\omega$.

Now: $X \in U_{\bot} \iff x \notin 0 \iff \exists k (e_k \subseteq x \iff x \in \bigcup_{k \neq 0} O_k)$

which is, as a union of elements of a base, indeed open. $\Box$

The following theorem was announced in Wadsworth [1973] for the $D_\infty$ case.

2.6. Theorem. Let $\mathcal{C}$ be $D_\infty^0$ or $P\omega$. Then $\mathcal{C}$ satisfies the range property.

Proof. Let $F$ be a closed term. Consider $BT(Fx)$.

Case 1. $x \notin BT(Fx)$. Then $BT(FM) = BT(F'M')$ for all $M, M'$. Since terms with equal Böhm trees are equal in $\mathcal{C}$, see Hyland [1975], Barendregt [1976], it follows that $Ra_{\mathcal{C}}(F)$ has cardinality 1.

Case 2. $x \in BT(Fx)$. Then by 1.4 $\lambda x. Fx \Downarrow x^\mathcal{C}$.

Since $[NQ]^\mathcal{C}$ can take arbitrary values in $\mathcal{C}$ when $N$ ranges over the closed terms, $Ra_{\mathcal{C}}(F)$ is infinite. $\Box$
2.6 Conjecture. $\mathcal{M}(\mathcal{H})$ satisfies the range property.

2.7 Question. Does every hard $\lambda$-algebra $\mathcal{M}$ (i.e. $\mathcal{M} = \mathcal{M}^\circ$) satisfy the range theorem?
§3. Duality

3.1 Def. Let \( f, g \) be two external functions on a \( \lambda \)-algebra \( \mathcal{M} = \langle M, \cdot \rangle \)

\( f, g \) are dual iff \( \forall a, b \in M: f(a) \cdot b = g(b) \cdot a \). Notation \( f \sim g \), or simply \( f \sim g \).

Remarks. (i) Let \( f \) be an external function on \( \mathcal{M} \). \( f \) is locally representable iff for each \( b \in M \) the function \( h \) defined by \( h(a) = f(a) \cdot b \) is representable. Then \( f \) is locally representable iff \( f \) has a dual. A model is rich iff all locally representable functions are representable.

(ii) If \( f \) is representable (by \( f \in \mathcal{M} \), say), then \( f \) has a dual \( g \) which is also representable (by \( g = \lambda ab. f_{ba} \)).

(iii) Let \( \mathcal{M} \) be extensional. Then \( f \) has at most one dual. Hence if \( f \sim g \) and \( f \) is representable, then by (ii) \( g \) is representable.

3.2 Def. \( \mathcal{M} \) is rich iff all dual functions on \( \mathcal{M} \) are representable in \( \mathcal{M} \).

3.3 Theorem. If \( \mathcal{M} \) is rich, then \( \mathcal{M} \) is extensional.

Proof. Suppose \( \mathcal{M} \) is not extensional. Then there exist \( b, b' \in M \) such that for all \( c \in M \) \( b \cdot c = b' \cdot c \) and \( b \neq b' \).

Define \( f(a) = \begin{cases} b' & \text{if } a = b \\ b & \text{else.} \end{cases} \)

and \( g = \lambda y. k(by) \),

then for all \( a, a' \in M \): \( f(a) \cdot a' = b \cdot a' = g(a') \cdot a \), hence \( f \sim g \).

But \( f \) cannot be representable since it has no fixed point. Thus \( \mathcal{M} \) is not rich. \( \Box \)

3.4 Cor. The following \( \lambda \)-algebras are not rich:

\( \mathcal{P} \omega; \mathcal{P}^{\omega}; \mathcal{M}(\lambda); \mathcal{M}^{\omega}(\lambda); \mathcal{M}^{\omega}(\lambda \eta) \).
Proof.

1. $P_\omega$ is not extensional:
Take for example $a = \{(0,0)\}$ and
\[ b = \{(0,0),(1,0)\} \]
Then $\forall c \in P_\omega a \cdot c = b \cdot c$ but $a \neq b$.

2. $P^0_\omega$ is not extensional: Let $I = \lambda x y . x y$, then
$P^0_\omega \not\vdash I x y = 1 x y$, but $P^0_\omega \vdash I = 1$. For otherwise
$P_\omega \vdash I = 1$, so $P_\omega \not\vdash \forall x y . x = \lambda y . x y$ which implies that $P_\omega$ were
extensional.

3. By the Church Rosser property $\lambda \not\vdash I = 1$. So $\mathcal{M}(\lambda)$, $\mathcal{M}_0(\lambda)$ are
not extensional.

4. $M^0(\lambda \eta)$ is not extensional because the $\lambda$-calculus is $\omega$-
incomplete, see Plotkin [1974].

3.5 Theorem. $D_\infty$ is rich.
Proof. Suppose that $f, g$ are dual i.e.:
\[ \forall a, b \in D_\infty: f(a) \cdot b = g(b) \cdot a. \]
We have to show that $f, g$ are representable.

It is sufficient to show that $f, g$ are continuous. Take a directed
$X \subseteq D_\infty$. For all $b \in D_\infty f(\{a\}) \cdot b = g(b) \cdot \{a\} = \bigcup\{w \cdot b \mid a \in X\} =
\bigcup\{f(a) \cdot b \mid a \in X\} = \bigcup\{f(a) \mid a \in X\} \cdot b$ by the duality condition and the
continuity of application.

Thus by extensionality in $D_\infty$: for all directed $X$ $f(\{a\}) = \bigcup\{f(a) \mid a \in X\}$
i.e. $f$ is continuous. The proof for $g$ is dual. $\square$

3.6 Theorem. $\mathcal{M}(\lambda \eta)$ is rich.
Proof. Define $M = \lambda \eta N$ iff $\lambda \eta \vdash M = N$ and $x \in \lambda \eta M$ iff for all $M' = \lambda \eta M$
one has $x \in \text{FV}(M')$.

Let $f, g$ be dual functions on $\mathcal{M}(\lambda \eta)$.
3.6.1 Lemma. (i) $x \in \lambda \eta \cdot \lambda y \cdot P \Rightarrow x \in \lambda \eta \cdot P$. (ii) Let $x \neq y$, then $x \in \lambda \eta \cdot M \iff x \in \lambda \eta \cdot My$.

Proof. (i) Let $x \in \lambda \eta \cdot \lambda y \cdot P$. Suppose $N = \lambda \eta \cdot P$, then $\lambda y \cdot N = \lambda \eta \cdot \lambda y \cdot P$. Therefore $x \in FV(\lambda y \cdot N) \subset FV(N)$.

(ii) $\Rightarrow$: Let $x \in \lambda \eta \cdot M$. Case 1. $M = \lambda \eta \cdot \lambda y \cdot P$. Then $x \in \lambda \eta \cdot \lambda y \cdot P$, so by (i) $x \in \lambda \eta \cdot P = \lambda \eta \cdot My$. Case 2. $M = \lambda \eta \cdot X \Rightarrow X$ is not of the form $\lambda y \cdot P$.

Suppose $N = My$. By the Church-Rosser theorem there is a $Z$ such that $\lambda \eta \cdot N \rightarrow Z$, $My \rightarrow Z$. Then $Z \equiv M' \cdot y$ and $M' = \lambda \eta \cdot M$. Therefore $x \in FV(M') \subset FV(Z) \subset FV(N)$.

$\Leftarrow$: Let $x \in \lambda \eta \cdot My$. Suppose $N = \lambda \eta \cdot M$. Then $Ny = \lambda \eta \cdot My$. Therefore $x \in FV(Ny)$ and hence $(x \neq y) x \in FV(N)$. $\equiv$ 3.6.1

3.6.2 Lemma. If $\exists y \neq x x \in \lambda \eta \cdot f(y)$, then $\forall y \neq x x \in \lambda \eta \cdot g(y)$ (and hence $\forall y \neq x x \in \lambda \eta \cdot f(y)$).

Proof. Suppose $x \in \lambda \eta \cdot f(y)$, $y \neq x$. Let $y' \neq x$. Then by 3.6.1 (ii) $x \in \lambda \eta \cdot f(y) \cdot y' = \lambda \eta \cdot g(y') \cdot y$. Hence, 3.6.1 (ii), $x \in \lambda \eta \cdot g(y')$. (The rest follows by applying the statement to $x \in \lambda \eta \cdot g(y)$). $\equiv$ 3.6.2

3.6.3 Main lemma. There is a variable $x$ such that for all terms $M$: $f(x)[x/M] = f(M)$.

Proof. Let $v$ be any variable. Choose $x \neq v$ such that $x \notin \lambda \eta \cdot f(v)$. Then $x \notin \lambda \eta \cdot g(z)$ for all $z \neq x$, by the dual of 3.6.2.

Given $M$, one can find a $y$ such that $y \notin \lambda \eta \cdot M$, $f(M), x, f(x)$. Hence $x \notin \lambda \eta \cdot g(y)$. Now since $y \neq x$ and $x \notin \lambda \eta \cdot g(y), (f(x)[x/M])y = (f(x) \cdot y)[x/M] = (g(y) \cdot x)[x/M] = g(y) \cdot M = f(M) \cdot y$.

Since $y \notin f(x), M, f(M)$, extensionality yields $f(x)[x/M] = f(M)$. $\equiv$ 3.6.

Now it follows by 3.6.3 that $f$ can be represented by the term $\lambda x \cdot f(x)$ and similarly for $g$. $\therefore$
The following construction is needed for the proof of \(3.10\).

3.7 Def. Let \(\#\) be a Gödel numbering of terms. \(\#M\) is the numeral \(\#M\).
A sequence of terms \(M_n\) is recursive if \(\lambda n.\#M_n\) is a recursive function.

3.8 Lemma. (Coding of infinite sequences). Let \(\{M_n\}\) be a recursive sequence of terms such that \(FV(M_n) \subseteq \{x\}\) for all \(n\). Then there exists a term \(X\) such that \(p^i X = M_i\) for all \(i\), where \(p\) is some closed term. Par abus de langage we write \(\langle M_n \rangle_{n \in \omega}\) for \(X\).

Proof.
As in Curry et al. [1972], 13 B3 there is a term \(E\) which enumerates all terms with \(x\) as only free variable:

\[ E(\#M) = M, \text{ for } M \text{ with } FV(M) = \{x\}. \]

Let \([M,N]\) be a pairing of terms defined by \(\lambda z.\#MN\). Then \([M,N](K) = M\) and \([M,N](KI) = N\). Define ordered tuples as follows: \([M] = M,\]
\[\begin{align*}
[M_1, \ldots, M_{n+1}] &= [M_1, [M_2, \ldots, M_{n+1}]].
\end{align*}\]
Let \(M\) with \(FV(M) \subseteq \{x\}\) be a recursive sequence of terms, i.e.

\(f = \lambda n.\#M_n\) is recursive. We want to code the sequence \(M^n\) as a \(\lambda\)-term. Let \(S^+\) be such that \(S^+ \overset{\eta}{\rightarrow} n+1\) and let \(b = \lambda xy. [E(Fy), (x(S^+y))]\),
where \(f\) \(\lambda\)-defines \(f\), and \(B = FP b\). Then
\[Bn \overset{\eta}{\rightarrow} bBn \overset{\eta}{\rightarrow} [E(Fn), Bn+1] \overset{\eta}{\rightarrow} [M_n, Bn+1].\]
So \(Bo = [M_0, B_1] = [M_0, M_1, B_2] = \ldots\). Hence by setting \(\langle M_n \rangle_{n \in \omega} = Bo\) we have a coding for infinite sequences of terms with one fixed free variable.

It is easy to construct a term \(p\) such that \(p^i \langle M_n \rangle_{n \in \omega} = M_m^i\)
(take e.g. \(pxa = \text{if zero } x \text{ then } a \text{ else } p(x-1)(a(Ki))\), using the fixed point theorem).

3.9 Lemma. For all closed \(Z\) there is an \(n\) such that \(Z \Omega^n = \Omega\).

\((Z \Omega^n\) is short for \(Z \Omega \ldots \Omega)\)

\(n\) times

Proof.
Case 1. \(Z\) is unsolvable; then \(Z = \Omega\), so \(n = 0\).
Case 2. \(Z\) is solvable; then \(Z\) has a HNF, \(Z = \lambda x.A_1 \ldots A_m\) \(x_i \in \bar{x}\).
Take \(n = i\), so \(Z\) \(\overset{\eta}{\rightarrow} \lambda x.\Omega A_1 \ldots A_m = \Omega.\)

3.10 Theorem. If \(\mathcal{M}\) is hard and sensible, then \(\mathcal{M}\) is not rich.

Proof. If \(\mathcal{M}\) is hard, then \(\mathcal{M}\) is isomorphic to \(\mathcal{M}^\circ(T)\), where \(T = \text{Th}(\mathcal{M})\).
We reason in \(\mathcal{M}^\circ(T)\). Since \(\mathcal{M}\) is sensible, \(\mathcal{M} \subseteq T\).
Let $h: \omega \to \omega$ be a function not definable in $\mathcal{M}$. $h$ exists since a hard model is countable.

Let $A_n(x, y) = x \sqcap \bigcap_{y}^{n}(y \sqcap \bigcap_{y}^{n}(y))$, $n \in \omega$. For closed $M$ the sequence $A_0(x, y), A_1(x, y), \ldots$ is by 3.9

$\emptyset(x_0), \emptyset(y_0), \ldots, \emptyset, \ldots$

where $n$ is such that $\emptyset^{n+1} = \emptyset$. Thus $\lambda n. A_n(x, y)$ is a recursive sequence containing one fixed free variable and hence representable as a term. Define $f(M) = \lambda y. \langle A_n(x, y) \rangle_{n \in \omega}$. Similarly, for closed $N$

$\lambda n. A_n(x, N) = \lambda x. \langle A_n(x, N) \rangle_{n \in \omega}$. Then for all closed $M, N$: $f(M)$ and $g(N)$ are well defined and $f(M) . N = g(N) . M = \langle A_n(M, N) \rangle_{n \in \omega}$ by construction. So $f$ and $g$ are dual.

Suppose now that $\mathcal{M}$ is rich, i.e. $f$ were representable by some closed $F$. Then for all closed $M, N$: $F \sqcap N = f(M) . N = \langle A_n(M, N) \rangle_{n \in \omega}$. But then $\emptyset \sqcap (F \sqcap N) = \emptyset \sqcap \langle h(n) \rangle_{n \in \omega} = h(n)$, hence $h$ were definable, contradiction. Thus $\mathcal{M}$ is not rich.

3.11 Corollary. $D^{\infty}$ and $\mathcal{M}^0(T)$ for $T \supseteq \mathcal{M}$ are poor.

3.12 Questions. (i). Is every extensional term model $\mathcal{M}(T)$ rich?

(ii). Is $\mathcal{M}^0(\lambda \omega)$ rich?

Here $\lambda \omega$ is the $\lambda$-theory obtained by adding the $\omega$-rule to the theory, see Barendregt [1974].
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