

# EXERCISES

## CHAPTER 4

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### 1. Reducted

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**Definition** Some rules for reference.

$$\begin{array}{c} \frac{}{\emptyset \vdash * : \square} \text{Sort} \qquad \frac{\Gamma \vdash A : s \quad x \notin \text{dom } \Gamma}{\Gamma, x : A \vdash x : A} \text{Var} \\[10pt] \frac{\Gamma \vdash A : B \quad \Gamma \vdash C : s \quad x \notin \text{dom } \Gamma}{\Gamma, x : C \vdash A : B} \text{Weak} \qquad \frac{\Gamma \vdash A : s \quad \Gamma \vdash B : s}{\Gamma \vdash A \rightarrow B : s} \text{Form} \\[10pt] \frac{\Gamma \vdash M : A \rightarrow B \quad \Gamma \vdash N : A}{\Gamma \vdash M N : B} \text{App} \\[10pt] \frac{\Gamma, x : A \vdash M : B \quad \Gamma \vdash A \rightarrow B : s}{\Gamma \vdash \lambda x : A . M : A \rightarrow B} \text{Abst} \\[10pt] \frac{\Gamma \vdash A : B \quad \Gamma \vdash B' : s \quad B \stackrel{\beta}{=} B'}{\Gamma \vdash A : B'} \text{Conv} \end{array}$$

Previously an alternative version of the flag derivation was used, only putting up a flag for a local premise (abstraction unwrapping) to save horizontal space.

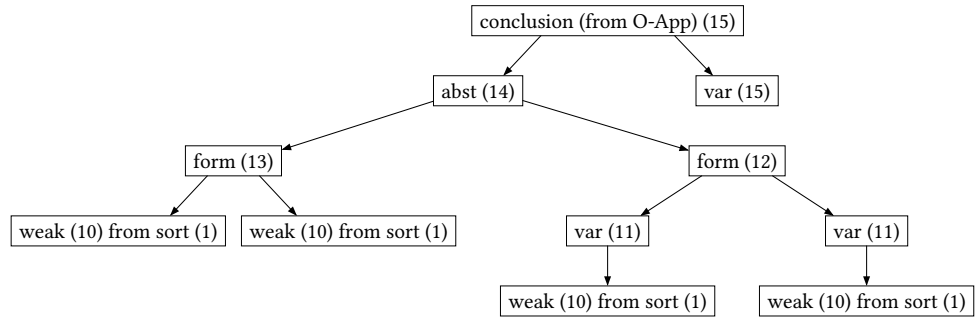
Currently, the standard flag derivation format will be used since now single lines will not be as long.

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### Problem

(4.1) Give a complete tree diagram of the derivation in section 4.5 (95)

*Solution.*



### Problem

(4.2 a) Give a complete  $\lambda\omega$  derivation in flag format of

$$\emptyset \vdash (* \rightarrow *) \rightarrow * : \square$$

*Solution.*

- |  |                 |
|--|-----------------|
| 1. $* : \square$                               | <b>Sort</b>     |
| 2. $* \rightarrow * : \square$                 | <b>1,1 Form</b> |
| 3. $(* \rightarrow *) \rightarrow * : \square$ | <b>2,1 Form</b> |

### Problem

(4.2 b) Give a complete  $\lambda\omega$  derivation in flag format of

$$\alpha : *, \beta : * \vdash (\alpha \rightarrow \beta) \rightarrow \alpha : *$$

*Solution.*

1.	$\emptyset \vdash * : \square$	<b>Sort</b>
2.	$\alpha : *$	
3.	$\alpha : *$	<b>1 Var</b>
4.	$* : \square$	<b>1,1 Weak</b>
5.	$\beta : *$	
6.	$\alpha : *$	<b>3,4 Weak</b>
7.	$\beta : *$	<b>4 Var</b>
8.	$\alpha \rightarrow \beta : *$	<b>6,7 Form</b>
9.	$(\alpha \rightarrow \beta) \rightarrow \alpha : *$	<b>8,6 Form</b>

### Problem

(4.3 a) Give a complete  $\lambda\omega$  derivation in flag format of

$$\alpha, \beta : *, x : \alpha, y : \alpha \rightarrow \beta \vdash y x : \beta$$

*Solution.*

1.	$* : \square$	<b>Sort</b>
2.	$\alpha : *$	
3.	$\alpha : *$	<b>1 Var</b>
4.	$* : \square$	<b>1,1 Weak</b>
5.	$\beta : *$	
6.	$\beta : *$	<b>4 Var</b>
7.	$\alpha : *$	<b>3,4 Weak</b>
8.	$* : \square$	<b>4,4 Weak</b>
9.	$x : \alpha$	
10.	$x : \alpha$	<b>7 Var</b>
11.	$\alpha : *$	<b>7,7 Weak</b>
12.	$\beta : *$	<b>6,7 Weak</b>
13.	$\alpha \rightarrow \beta : *$	<b>11,12 Form</b>
14.	$y : \alpha \rightarrow \beta$	
15.	$y : \alpha \rightarrow \beta$	<b>13 Var</b>
16.	$x : \alpha$	<b>10,13 Weak</b>
17.	$y x : \beta$	<b>15,16 App</b>

## Problem

(4.3 b) Give a shortened  $\lambda_{\omega}$  derivation in flag format of

$$\alpha, \beta : *, x : \alpha, y : \alpha \rightarrow \beta, z : \beta \rightarrow \alpha \vdash z (y x) : \alpha$$

(4.3 b) Give a shortened  $\lambda_{\omega}$  derivation in flag format of

$$\alpha, \beta : *, x : \alpha, y : \alpha \rightarrow \beta, z : \beta \rightarrow \alpha \vdash z (y x) : \alpha$$

*Solution.*

1.	$\alpha : *$			
2.	$\beta : *$			
3.	$x : \alpha$			
4.	$y : \alpha \rightarrow \beta$			
5.	$x : \alpha$			<b>3 Weak</b>
6.	$z : \beta \rightarrow \alpha$			
7.	$x : \alpha$			<b>5 Weak</b>
8.	$y : \alpha \rightarrow \beta$			<b>4 Weak</b>
9.	$y\ x : \beta$			<b>8,7 App</b>
10.	$z\ (y\ x) : \alpha$			<b>6,9 App</b>

## Problem

(4.4 a) Give a shortened  $\lambda_{\omega}$  derivation in flag format of

$$\alpha : *, \beta : * \rightarrow * \vdash \beta(\beta\alpha) : *$$

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$$\alpha : *, \beta : * \rightarrow * \vdash \beta(\beta\alpha) : *$$

*Solution.*

$$\begin{array}{lcl}
1. & \alpha : * & \\
2. & \left| \beta : * \rightarrow * \right. & \\
3. & \left| \left| \beta\alpha : * \right. \right. & \mathbf{2,1 \text{ App}} \\
4. & \left| \left| \beta(\beta\alpha) : * \right. \right. & \mathbf{2,4 \text{ App}}
\end{array}$$

## Problem

(4.4 b) Give a shortened  $\lambda\underline{\omega}$  derivation in flag format of

$$\alpha : *, \beta : * \rightarrow *, x : \beta(\beta\alpha) \vdash \lambda y : \alpha. x : \alpha \rightarrow \beta(\beta\alpha)$$

(4.4 b) Give a shortened  $\lambda\underline{\omega}$  derivation in flag format of

$$\alpha : *, \beta : * \rightarrow *, x : \beta(\beta\alpha) \vdash \lambda y : \alpha. x : \alpha \rightarrow \beta(\beta\alpha)$$

*Solution.*

$$\begin{array}{lcl}
 1. & \alpha : * & \\
 2. & \left| \beta : * \rightarrow * \right. & \\
 3. & \left| \left| x : \beta(\beta\alpha) \right. \right. & \\
 4. & \left| \left| \left| y : \alpha \right. \right. \right. & \\
 5. & \left| \left| \left| \left| x : \beta(\beta\alpha) \right. \right. \right. & \mathbf{3 \text{ Var}} \\
 6. & \left| \left| \left| \left| \lambda y : \alpha. x : \alpha \rightarrow \beta(\beta\alpha) \right. \right. \right. & \mathbf{5 \text{ Abst}}
 \end{array}$$

### Problem

(4.4 c) Give a shortened  $\lambda\omega$  derivation in flag format of

$$\emptyset \vdash \lambda\alpha : *. \lambda\beta : * \rightarrow *. \beta(\beta\alpha) : * \rightarrow (* \rightarrow *) \rightarrow *$$

*Solution.*

$$\begin{array}{lcl}
 1. & \alpha : * & \\
 2. & \left| \beta : * \rightarrow * \right. & \\
 3. & \left| \left| \beta\alpha : * \right. \right. & \mathbf{2,1 \text{ App}} \\
 4. & \left| \left| \left| \beta(\beta\alpha) : * \right. \right. \right. & \mathbf{2,3 \text{ App}} \\
 5. & \left| \left| \left| \lambda\beta : * \rightarrow *. \beta(\beta\alpha) : (* \rightarrow *) \rightarrow * \right. \right. \right. & \mathbf{4 \text{ Abst}} \\
 6. & \lambda\alpha : *. \lambda\beta : * \rightarrow *. \beta(\beta\alpha) : * \rightarrow (* \rightarrow *) \rightarrow * & \mathbf{5 \text{ Abst}}
 \end{array}$$

### Problem

(4.4 d) Give a shortened  $\lambda\omega$  derivation in flag format of

$$\mathbf{nat} : * \vdash (\lambda\alpha : *. \lambda\beta : * \rightarrow *. \beta(\beta\alpha)) \mathbf{nat} (\lambda\gamma : *. \gamma) : *$$

*Solution.*

$$\begin{array}{lcl}
 1. & \mathbf{nat} : * & \\
 2. & \left| \alpha : * \right. & \\
 3. & \left| \left| \beta : * \rightarrow * \right. \right. & \\
 4. & \left| \left| \left| \beta\alpha : * \right. \right. \right. & \mathbf{3,2 \text{ App}} \\
 5. & \left| \left| \left| \left| \beta(\beta\alpha) : * \right. \right. \right. & \mathbf{3,4 \text{ App}} \\
 6. & \left| \left| \left| \lambda\beta : * \rightarrow *. \beta(\beta\alpha) : (* \rightarrow *) \rightarrow * \right. \right. \right. & \mathbf{5 \text{ Abst}}
 \end{array}$$

7.	$\lambda\alpha : * . \lambda\beta : * \rightarrow * . \beta(\beta\alpha) : * \rightarrow (* \rightarrow *) \rightarrow *$	<b>6 Abst</b>
8.	$(\lambda\alpha : * . \lambda\beta : * \rightarrow * . \beta(\beta\alpha)) \text{ nat} : (* \rightarrow *) \rightarrow *$	<b>7,1 App</b>
9.	$\gamma : *$	
10.	$\boxed{\gamma : *}$	<b>9 Var</b>
11.	$\lambda\gamma : * . \gamma : * \rightarrow *$	<b>10 Abst</b>
12.	$(\lambda\alpha : * . \lambda\beta : * \rightarrow * . \beta(\beta\alpha)) \text{ nat} (\lambda\gamma : * . \gamma) : *$	<b>8,11 App</b>

### Problem

(4.5) Give a shortened  $\lambda\omega$  derivation in flag format of

$$\alpha : * . x : \alpha \vdash \lambda y : \alpha . x : (\lambda\beta : * . \beta \rightarrow \beta)\alpha$$

*Solution.*

1.	$\alpha : *$	
2.	$x : \alpha$	
3.	$y : \alpha$	
4.	$\boxed{x : \alpha}$	<b>2 Weak</b>
5.	$\lambda y : \alpha . x : \alpha \rightarrow \alpha$	<b>4 Abst</b>
6.	$\beta : *$	
7.	$\boxed{\beta \rightarrow \beta : *}$	<b>6,6 Form</b>
8.	$\lambda\beta : * . \beta \rightarrow \beta : * \rightarrow *$	<b>7 Abst</b>
9.	$(\lambda\beta : * . \beta \rightarrow \beta)\alpha : *$	<b>8,1 App</b>
10.	$\boxed{\lambda y : \alpha . x : (\lambda\beta : * . \beta \rightarrow \beta)\alpha}$	<b>5,9 Conv</b>

### Problem

(4.6 a) Show that no such context  $\Gamma$  and term  $M$  in  $\lambda\omega$  such that

$$\Gamma \vdash \square : M$$

is derivable.

*Solution.* Proof by induction on inference rules. Rules like Sort, Var, Form, Abst, App has syntactically or semantic different conclusions than  $\square : M$ .

*Case 1 : Rule Weak.* Let  $\Gamma', C : s \equiv \Gamma$ . Therefore this derivation requires a premise  $\Gamma' \vdash \square : M$ . By the inductive hypothesis this is impossible. ■

*Case 2 : Rule Conv.* This derivation requires a premise  $\Gamma \vdash \square : M'$  such that  $M \underset{\beta}{=} M'$ . By the inductive hypothesis this is impossible. ■

By the principle of induction this proves that there's no derivation that could give  $\Gamma \vdash \square : M$ .

### Problem

(4.6 b) Prove there are no such context  $\Gamma$  and terms  $M$  and  $N$  in  $\lambda\omega$  such that

$$\Gamma \vdash M \rightarrow \square : N$$

*Solution.* Proof by induction on inference rules. Rules like Sort, Var, Abst, App has syntactically or semantically conclusions than  $M \rightarrow \square : N$ .

*Case 1 : Rule Weak.* Let  $\Gamma', C : s \equiv \Gamma$ . The derivation requires a premise  $\Gamma' \vdash M \rightarrow \square : N$ . By the inductive hypothesis this is impossible. ■

*Case 2 : Rule Form.* This requires a derivation with premise  $\Gamma \vdash \square : N$ , which by 4.6 a is not possible. ■

*Case 3 : Rule Conv.* This requires a premise  $\Gamma \vdash M \rightarrow \square : N'$  such that  $N \equiv N'$ . By the inductive hypothesis this is impossible. ■

By the principle of induction this proves there's no derivation that could give  $\Gamma \vdash M \rightarrow \square : N$ .