

Axioms Systems for Category Theory in Free Logic

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1 Introduction

This document provides a concise overview on the core results of our previous work [2, 3, 1] on the exploration of axiom systems for category theory. Extending the previous studies we include one further axiomatic theory in our experiments. This additional theory has been suggested by Mac Lane [5] in 1948. We show that the axioms proposed by Mac Lane are equivalent to the ones studied in [3], which includes an axioms set suggested by Scott [6] in the 1970s and another axioms set proposed by Freyd and Scedrov [4] in 1990, which we slightly modified in [3] to remedy a minor technical issue. The explanations given below are minimal, for more details we refer to the referenced papers, in particular, to [3].

2 Embedding of Free Logic in HOL

We introduce a shallow semantical embedding of free logic [3] in Isabelle/HOL. Definite description is omitted, since it is not needed in the studies below and also since the definition provided in [1] introduces the here undesired commitment that at least one non-existing element of type i is a priori given. We here want to consider this an optional condition.

typedecl i — Type for individuals

consts $fExistence:: i \Rightarrow bool$ (E) — Existence/definedness predicate in free logic

abbreviation $fNot$ (\neg) **where** $\neg\varphi \equiv \neg\varphi$
abbreviation $fImpl$ (**infixr** \rightarrow 13) **where** $\varphi \rightarrow \psi \equiv \varphi \longrightarrow \psi$
abbreviation fId (**infixr** $=$ 25) **where** $l = r \equiv l = r$
abbreviation $fAll$ (\forall) **where** $\forall\Phi \equiv \forall x. E\ x \longrightarrow \Phi\ x$
abbreviation $fAllBi$ (**binder** \forall [8]9) **where** $\forall x. \varphi\ x \equiv \forall\varphi$
abbreviation fOr (**infixr** \vee 21) **where** $\varphi \vee \psi \equiv (\neg\varphi) \rightarrow \psi$
abbreviation $fAnd$ (**infixr** \wedge 22) **where** $\varphi \wedge \psi \equiv \neg(\neg\varphi \vee \neg\psi)$
abbreviation $fImpli$ (**infixr** \leftarrow 13) **where** $\varphi \leftarrow \psi \equiv \psi \rightarrow \varphi$
abbreviation $fEquiv$ (**infixr** \leftrightarrow 15) **where** $\varphi \leftrightarrow \psi \equiv (\varphi \rightarrow \psi) \wedge (\psi \rightarrow \varphi)$
abbreviation fEx (\exists) **where** $\exists\Phi \equiv \neg(\forall(\lambda y. \neg(\Phi\ y)))$
abbreviation $fExiBi$ (**binder** \exists [8]9) **where** $\exists x. \varphi\ x \equiv \exists\varphi$

3 Some Basic Notions in Category Theory

Morphisms in the category are modeled as objects of type i . We introduce three partial functions, dom (domain), cod (codomain), and morphism composition (\cdot) .

For composition we assume set-theoretical composition here (i.e., functional composition from right to left).

consts

$domain:: i \Rightarrow i$ (dom - [108] 109)

$codomain:: i \Rightarrow i$ (cod - [110] 111)

$composition:: i \Rightarrow i \Rightarrow i$ (**infix** \cdot 110)

— Kleene Equality

abbreviation $KLEq$ (**infixr** \cong 56) **where** $x \cong y \equiv (E\ x \vee E\ y) \rightarrow x = y$

— Existing Identity

abbreviation $ExId$ (**infixr** \simeq 56) **where** $x \simeq y \equiv (E\ x \wedge E\ y \wedge x = y)$

— Identity-morphism: see also p. 4. of [4].

abbreviation $ID\ i \equiv (\forall x. E(i \cdot x) \rightarrow i \cdot x \cong x) \wedge (\forall x. E(x \cdot i) \rightarrow x \cdot i \cong x)$

— Identity-morphism: Mac Lane's definition, the same as ID except for notion of equality.

abbreviation $IDMcL\ \varrho \equiv (\forall \alpha. E(\varrho \cdot \alpha) \rightarrow \varrho \cdot \alpha = \alpha) \wedge (\forall \beta. E(\beta \cdot \varrho) \rightarrow \beta \cdot \varrho = \beta)$

— The two notions of identity-morphisms are obviously equivalent.

lemma $IDPredicates: ID \equiv IDMcL$ **by** *auto*

4 The Axioms Sets studied by Benz Müller and Scott [3]

4.1 AxiomsSet1

AxiomsSet1 generalizes the notion of a monoid by introducing a partial, strict binary composition operation “ \cdot ”. The existence of left and right identity elements is addressed in axioms C_i and D_i . The notions of *dom* (domain) and *cod* (codomain) abstract from their common meaning in the context of sets. In category theory we work with just a single type of objects (the type i in our setting) and therefore identity morphisms are employed to suitably characterize their meanings.

locale *AxiomsSet1* =

assumes

$S_i: E(x \cdot y) \rightarrow (E x \wedge E y)$ **and**

$E_i: E(x \cdot y) \leftarrow (E x \wedge E y \wedge (\exists z. z \cdot z \cong z \wedge x \cdot z \cong x \wedge z \cdot y \cong y))$ **and**

$A_i: x \cdot (y \cdot z) \cong (x \cdot y) \cdot z$ **and**

$C_i: \forall y. \exists i. ID i \wedge i \cdot y \cong y$ **and**

$D_i: \forall x. \exists j. ID j \wedge x \cdot j \cong x$

begin

lemma *True nitpick* [*satisfy*] **oops** — Consistency

lemma **assumes** $\exists x. \neg(E x)$ **shows** *True nitpick* [*satisfy*] **oops** — Consistency

lemma **assumes** $(\exists x. \neg(E x)) \wedge (\exists x. (E x))$ **shows** *True nitpick* [*satisfy*] **oops** — Consistency

lemma $E_i \text{Impl}: E(x \cdot y) \rightarrow (E x \wedge E y \wedge (\exists z. z \cdot z \cong z \wedge x \cdot z \cong x \wedge z \cdot y \cong y))$ **by** (*metis* $A_i C_i S_i$)
— Uniqueness of i and j in the latter two axioms.

lemma $UC_i: \forall y. \exists i. ID i \wedge i \cdot y \cong y \wedge (\forall j. (ID j \wedge j \cdot y \cong y) \rightarrow i \cong j)$ **by** (*smt* $A_i C_i S_i$)

lemma $UD_i: \forall x. \exists j. ID j \wedge x \cdot j \cong x \wedge (\forall i. (ID i \wedge x \cdot i \cong x) \rightarrow j \cong i)$ **by** (*smt* $A_i D_i S_i$)

— But i and j need not to equal.

lemma $(\exists C D. (\forall y. ID (C y) \wedge (C y) \cdot y \cong y) \wedge (\forall x. ID (D x) \wedge x \cdot (D x) \cong x) \wedge \neg(D = C))$

nitpick [*satisfy*] **oops** — Model found

lemma $(\exists x. E x) \wedge (\exists C D. (\forall y. ID (C y) \wedge (C y) \cdot y \cong y) \wedge (\forall x. ID (D x) \wedge x \cdot (D x) \cong x) \wedge \neg(D = C))$

nitpick [*satisfy*] **oops** — Model found

end

4.2 AxiomsSet2

AxiomsSet2 is developed from AxiomsSet1 by Skolemization of the existentially quantified variables i and j in axioms C_i and D_i . We can argue semantically that every model of AxiomsSet1 has such functions. Hence, we get a conservative extension of AxiomsSet1. The strictness axiom S is extended, so that strictness is now also postulated for the new Skolem functions *dom* and *cod*.

locale *AxiomsSet2* =

assumes

$S_{ii}: (E(x \cdot y) \rightarrow (E x \wedge E y)) \wedge (E(\text{dom } x) \rightarrow E x) \wedge (E(\text{cod } y) \rightarrow E y)$ **and**

$E_{ii}: E(x \cdot y) \leftarrow (E x \wedge E y \wedge (\exists z. z \cdot z \cong z \wedge x \cdot z \cong x \wedge z \cdot y \cong y))$ **and**

$A_{ii}: x \cdot (y \cdot z) \cong (x \cdot y) \cdot z$ **and**

$C_{ii}: E y \rightarrow (ID(\text{cod } y) \wedge (\text{cod } y) \cdot y \cong y)$ **and**

$D_{ii}: E x \rightarrow (ID(\text{dom } x) \wedge x \cdot (\text{dom } x) \cong x)$

begin

lemma *True nitpick* [*satisfy*] **oops** — Consistency

lemma **assumes** $\exists x. \neg(E x)$ **shows** *True nitpick* [*satisfy*] **oops** — Consistency

lemma **assumes** $(\exists x. \neg(E x)) \wedge (\exists x. (E x))$ **shows** *True nitpick* [*satisfy*] **oops** — Consistency

lemma $E_{ii} \text{Impl}: E(x \cdot y) \rightarrow (E x \wedge E y \wedge (\exists z. z \cdot z \cong z \wedge x \cdot z \cong x \wedge z \cdot y \cong y))$ **by** (*metis* $A_{ii} C_{ii} S_{ii}$)

lemma $\text{domTotal}: E x \rightarrow E(\text{dom } x)$ **by** (*metis* $D_{ii} S_{ii}$)

lemma $\text{codTotal}: E x \rightarrow E(\text{cod } x)$ **by** (*metis* $C_{ii} S_{ii}$)

end

4.2.1 AxiomsSet2 entails AxiomsSet1

context *AxiomsSet2*

begin

```

lemma  $S_i$ :  $E(x \cdot y) \rightarrow (E x \wedge E y)$  using  $S_{ii}$  by blast
lemma  $E_i$ :  $E(x \cdot y) \leftarrow (E x \wedge E y \wedge (\exists z. z \cdot z \cong z \wedge x \cdot z \cong x \wedge z \cdot y \cong y))$  using  $E_{ii}$  by blast
lemma  $A_i$ :  $x \cdot (y \cdot z) \cong (x \cdot y) \cdot z$  using  $A_{ii}$  by blast
lemma  $C_i$ :  $\forall y. \exists i. ID i \wedge i \cdot y \cong y$  by (metis  $C_{ii}$   $S_{ii}$ )
lemma  $D_i$ :  $\forall x. \exists j. ID j \wedge x \cdot j \cong x$  by (metis  $D_{ii}$   $S_{ii}$ )
end

```

4.2.2 AxiomsSet1 entails AxiomsSet2 (by semantic means)

By semantic means (Skolemization).

4.3 AxiomsSet3

In AxiomsSet3 the existence axiom E_{ii} from AxiomsSet2 is simplified by taking advantage of the two new Skolem functions dom and cod .

The left-to-right direction of existence axiom E_{iii} is implied.

```

locale AxiomsSet3 =
  assumes
     $S_{iii}$ :  $(E(x \cdot y) \rightarrow (E x \wedge E y)) \wedge (E(dom x) \rightarrow E x) \wedge (E(cod y) \rightarrow E y)$  and
     $E_{iii}$ :  $E(x \cdot y) \leftarrow (dom x \cong cod y \wedge E(cod y))$  and
     $A_{iii}$ :  $x \cdot (y \cdot z) \cong (x \cdot y) \cdot z$  and
     $C_{iii}$ :  $E y \rightarrow (ID(cod y) \wedge (cod y) \cdot y \cong y)$  and
     $D_{iii}$ :  $E x \rightarrow (ID(dom x) \wedge x \cdot (dom x) \cong x)$ 
  begin
    lemma True nitpick [satisfy] oops — Consistency
    lemma assumes  $\exists x. \neg(E x)$  shows True nitpick [satisfy] oops — Consistency
    lemma assumes  $(\exists x. \neg(E x)) \wedge (\exists x. (E x))$  shows True nitpick [satisfy] oops — Consistency

    lemma  $E_{iii}Impl$ :  $E(x \cdot y) \rightarrow (dom x \cong cod y \wedge E(cod y))$  by (metis (full-types)  $A_{iii}$   $C_{iii}$   $D_{iii}$   $S_{iii}$ )
  end

```

4.3.1 AxiomsSet3 entails AxiomsSet2

```

context AxiomsSet3
begin
  lemma  $S_{ii}$ :  $(E(x \cdot y) \rightarrow (E x \wedge E y)) \wedge (E(dom x) \rightarrow E x) \wedge (E(cod y) \rightarrow E y)$  using  $S_{iii}$  by blast
  lemma  $E_{ii}$ :  $E(x \cdot y) \leftarrow (E x \wedge E y \wedge (\exists z. z \cdot z \cong z \wedge x \cdot z \cong x \wedge z \cdot y \cong y))$  by (metis  $A_{iii}$   $C_{iii}$   $D_{iii}$   $E_{iii}$   $S_{iii}$ )
  lemma  $A_i$ :  $x \cdot (y \cdot z) \cong (x \cdot y) \cdot z$  using  $A_{iii}$  by blast
  lemma  $C_{ii}$ :  $E y \rightarrow (ID(cod y) \wedge (cod y) \cdot y \cong y)$  using  $C_{iii}$  by auto
  lemma  $D_{ii}$ :  $E x \rightarrow (ID(dom x) \wedge x \cdot (dom x) \cong x)$  using  $D_{iii}$  by auto
end

```

4.3.2 AxiomsSet2 entails AxiomsSet3

```

context AxiomsSet2
begin
  lemma  $S_{iii}$ :  $(E(x \cdot y) \rightarrow (E x \wedge E y)) \wedge (E(dom x) \rightarrow E x) \wedge (E(cod y) \rightarrow E y)$  using  $S_{ii}$  by blast
  lemma  $E_{iii}$ :  $E(x \cdot y) \leftarrow (dom x \cong cod y \wedge E(cod y))$  by (metis  $C_{ii}$   $D_{ii}$   $E_{ii}$   $S_{ii}$ )
  lemma  $A_{iii}$ :  $x \cdot (y \cdot z) \cong (x \cdot y) \cdot z$  using  $A_{ii}$  by blast
  lemma  $C_{iii}$ :  $E y \rightarrow (ID(cod y) \wedge (cod y) \cdot y \cong y)$  using  $C_{ii}$  by auto
  lemma  $D_{iii}$ :  $E x \rightarrow (ID(dom x) \wedge x \cdot (dom x) \cong x)$  using  $D_{ii}$  by auto
end

```

4.4 The Axioms Set AxiomsSet4

AxiomsSet4 simplifies the axioms C_{iii} and D_{iii} . However, as it turned out, these simplifications also require the existence axiom E_{iii} to be strengthened into an equivalence.

```

locale AxiomsSet4 =

```

```

assumes
   $S_{iv}: (E(x \cdot y) \rightarrow (E x \wedge E y)) \wedge (E(\text{dom } x) \rightarrow E x) \wedge (E(\text{cod } y) \rightarrow E y)$  and
   $E_{iv}: E(x \cdot y) \leftrightarrow (\text{dom } x \cong \text{cod } y \wedge E(\text{cod } y))$  and
   $A_{iv}: x \cdot (y \cdot z) \cong (x \cdot y) \cdot z$  and
   $C_{iv}: (\text{cod } y) \cdot y \cong y$  and
   $D_{iv}: x \cdot (\text{dom } x) \cong x$ 
begin
  lemma True nitpick [satisfy] oops — Consistency
  lemma assumes  $\exists x. \neg(E x)$  shows True nitpick [satisfy] oops — Consistency
  lemma assumes  $(\exists x. \neg(E x)) \wedge (\exists x. (E x))$  shows True nitpick [satisfy] oops — Consistency
end

```

4.4.1 AxiomsSet4 entails AxiomsSet3

```

context AxiomsSet4
begin
  lemma  $S_{iii}: (E(x \cdot y) \rightarrow (E x \wedge E y)) \wedge (E(\text{dom } x) \rightarrow E x) \wedge (E(\text{cod } y) \rightarrow E y)$  using  $S_{iv}$  by blast
  lemma  $E_{iii}: E(x \cdot y) \leftrightarrow (\text{dom } x \cong \text{cod } y \wedge E(\text{cod } y))$  using  $E_{iv}$  by blast
  lemma  $A_{iii}: x \cdot (y \cdot z) \cong (x \cdot y) \cdot z$  using  $A_{iv}$  by blast
  lemma  $C_{iii}: E y \rightarrow (ID(\text{cod } y) \wedge (\text{cod } y) \cdot y \cong y)$  by (metis  $C_{iv}$   $D_{iv}$   $E_{iv}$ )
  lemma  $D_{iii}: E x \rightarrow (ID(\text{dom } x) \wedge x \cdot (\text{dom } x) \cong x)$  by (metis  $C_{iv}$   $D_{iv}$   $E_{iv}$ )
end

```

4.4.2 AxiomsSet3 entails AxiomsSet4

```

context AxiomsSet3
begin
  lemma  $S_{iv}: (E(x \cdot y) \rightarrow (E x \wedge E y)) \wedge (E(\text{dom } x) \rightarrow E x) \wedge (E(\text{cod } y) \rightarrow E y)$  using  $S_{iii}$  by blast
  lemma  $E_{iv}: E(x \cdot y) \leftrightarrow (\text{dom } x \cong \text{cod } y \wedge E(\text{cod } y))$  by (metis (full-types)  $A_{iii}$   $C_{iii}$   $D_{iii}$   $E_{iii}$   $S_{iii}$ )
  lemma  $A_{iv}: x \cdot (y \cdot z) \cong (x \cdot y) \cdot z$  using  $A_{iii}$  by blast
  lemma  $C_{iv}: (\text{cod } y) \cdot y \cong y$  using  $C_{iii}$   $S_{iii}$  by blast
  lemma  $D_{iv}: x \cdot (\text{dom } x) \cong x$  using  $D_{iii}$   $S_{iii}$  by blast
end

```

4.5 AxiomsSet5

AxiomsSet5 has been proposed by Scott [6] in the 1970s. This set of axioms is equivalent to the axioms set presented by Freyd and Scedrov in their textbook “Categories, Allegories” [4] when encoded in free logic, corrected/adapted and further simplified, see Section 5.

```

locale AxiomsSet5 =
assumes
   $S1: E(\text{dom } x) \rightarrow E x$  and
   $S2: E(\text{cod } y) \rightarrow E y$  and
   $S3: E(x \cdot y) \leftrightarrow \text{dom } x \cong \text{cod } y$  and
   $S4: x \cdot (y \cdot z) \cong (x \cdot y) \cdot z$  and
   $S5: (\text{cod } y) \cdot y \cong y$  and
   $S6: x \cdot (\text{dom } x) \cong x$ 
begin
  lemma True nitpick [satisfy] oops — Consistency
  lemma assumes  $\exists x. \neg(E x)$  shows True nitpick [satisfy] oops — Consistency
  lemma assumes  $(\exists x. \neg(E x)) \wedge (\exists x. (E x))$  shows True nitpick [satisfy] oops — Consistency
end

```

4.5.1 AxiomsSet5 entails AxiomsSet4

```

context AxiomsSet5
begin
  lemma  $S_{iv}: (E(x \cdot y) \rightarrow (E x \wedge E y)) \wedge (E(\text{dom } x) \rightarrow E x) \wedge (E(\text{cod } y) \rightarrow E y)$  using  $S1$   $S2$   $S3$  by blast
  lemma  $E_{iv}: E(x \cdot y) \leftrightarrow (\text{dom } x \cong \text{cod } y \wedge E(\text{cod } y))$  using  $S3$  by metis
  lemma  $A_{iv}: x \cdot (y \cdot z) \cong (x \cdot y) \cdot z$  using  $S4$  by blast

```

```

lemma  $C_{iv}$ :  $(cod\ y) \cdot y \cong y$  using  $S5$  by blast
lemma  $D_{iv}$ :  $x \cdot (dom\ x) \cong x$  using  $S6$  by blast
end

```

4.5.2 AxiomsSet4 entails AxiomsSet5

```

context AxiomsSet4
begin
lemma  $S1$ :  $E(dom\ x) \rightarrow E\ x$  using  $S_{iv}$  by blast
lemma  $S2$ :  $E(cod\ y) \rightarrow E\ y$  using  $S_{iv}$  by blast
lemma  $S3$ :  $E(x \cdot y) \leftrightarrow dom\ x \simeq cod\ y$  using  $E_{iv}$  by metis
lemma  $S4$ :  $x \cdot (y \cdot z) \cong (x \cdot y) \cdot z$  using  $A_{iv}$  by blast
lemma  $S5$ :  $(cod\ y) \cdot y \cong y$  using  $C_{iv}$  by blast
lemma  $S6$ :  $x \cdot (dom\ x) \cong x$  using  $D_{iv}$  by blast
end

```

5 The Axioms Sets by Freyd and Scedrov [4]

5.1 AxiomsSet6

The axioms by Freyd and Scedrov [4] in our notation, when being corrected (cf. the modification in axiom A1).

Freyd and Scedrov employ a different notation for $dom\ x$ and $cod\ x$. They denote these operations by $\square x$ and $x\square$. Moreover, they employ diagrammatic composition instead of the set-theoretic definition (functional composition from right to left) used so far. We leave it to the reader to verify that their axioms corresponds to the axioms presented here modulo an appropriate conversion of notation.

```

locale AxiomsSet6 =
  assumes
     $A1$ :  $E(x \cdot y) \leftrightarrow dom\ x \simeq cod\ y$  and
     $A2a$ :  $cod(dom\ x) \cong dom\ x$  and
     $A2b$ :  $dom(cod\ y) \cong cod\ y$  and
     $A3a$ :  $x \cdot (dom\ x) \cong x$  and
     $A3b$ :  $(cod\ y) \cdot y \cong y$  and
     $A4a$ :  $dom(x \cdot y) \cong dom((dom\ x) \cdot y)$  and
     $A4b$ :  $cod(x \cdot y) \cong cod(x \cdot (cod\ y))$  and
     $A5$ :  $x \cdot (y \cdot z) \cong (x \cdot y) \cdot z$ 
  begin
lemma True nitpick [satisfy] oops — Consistency
lemma assumes  $\exists x. \neg(E\ x)$  shows True nitpick [satisfy] oops — Consistency
lemma assumes  $(\exists x. \neg(E\ x)) \wedge (\exists x. (E\ x))$  shows True nitpick [satisfy] oops — Consistency
end

```

5.1.1 AxiomsSet6 entails AxiomsSet5

```

context AxiomsSet6
begin
lemma  $S1$ :  $E(dom\ x) \rightarrow E\ x$  by (metis A1 A2a A3a)
lemma  $S2$ :  $E(cod\ y) \rightarrow E\ y$  using  $A1\ A2b\ A3b$  by metis
lemma  $S3$ :  $E(x \cdot y) \leftrightarrow dom\ x \simeq cod\ y$  by (metis A1)
lemma  $S4$ :  $x \cdot (y \cdot z) \cong (x \cdot y) \cdot z$  using  $A5$  by blast
lemma  $S5$ :  $(cod\ y) \cdot y \cong y$  using  $A3b$  by blast
lemma  $S6$ :  $x \cdot (dom\ x) \cong x$  using  $A3a$  by blast

lemma  $A4aRedundant$ :  $dom(x \cdot y) \cong dom((dom\ x) \cdot y)$  using  $A1\ A2a\ A3a\ A5$  by metis
lemma  $A4bRedundant$ :  $cod(x \cdot y) \cong cod(x \cdot (cod\ y))$  using  $A1\ A2b\ A3b\ A5$  by smt
lemma  $A2aRedundant$ :  $cod(dom\ x) \cong dom\ x$  using  $A1\ A3a\ A3b\ A4a\ A4b$  by smt
lemma  $A2bRedundant$ :  $dom(cod\ y) \cong cod\ y$  using  $A1\ A3a\ A3b\ A4a\ A4b$  by smt
end

```

5.1.2 AxiomsSet5 entails AxiomsSet6

```

context AxiomsSet5
begin
lemma A1:  $E(x \cdot y) \leftrightarrow \text{dom } x \cong \text{cod } y$  using S3 by blast
lemma A2:  $\text{cod}(\text{dom } x) \cong \text{dom } x$  by (metis S1 S2 S3 S6)
lemma A2b:  $\text{dom}(\text{cod } y) \cong \text{cod } y$  using S1 S2 S3 S5 by metis
lemma A3a:  $x \cdot (\text{dom } x) \cong x$  using S6 by auto
lemma A3b:  $(\text{cod } y) \cdot y \cong y$  using S5 by blast
lemma A4a:  $\text{dom}(x \cdot y) \cong \text{dom}((\text{dom } x) \cdot y)$  by (metis S1 S3 S4 S5 S6)
lemma A4b:  $\text{cod}(x \cdot y) \cong \text{cod}(x \cdot (\text{cod } y))$  by (metis (full-types) S2 S3 S4 S5 S6)
lemma A5:  $x \cdot (y \cdot z) \cong (x \cdot y) \cdot z$  using S4 by blast
end

```

5.2 AxiomsSet7 (technically flawed)

The axioms by Freyd and Scedrov in our notation, without the suggested correction of axiom A1. This axioms set is technically flawed when encoded in our given context. It leads to a constricted inconsistency.

```

locale AxiomsSet7 =
assumes
  A1:  $E(x \cdot y) \leftrightarrow \text{dom } x \cong \text{cod } y$  and
  A2a:  $\text{cod}(\text{dom } x) \cong \text{dom } x$  and
  A2b:  $\text{dom}(\text{cod } y) \cong \text{cod } y$  and
  A3a:  $x \cdot (\text{dom } x) \cong x$  and
  A3b:  $(\text{cod } y) \cdot y \cong y$  and
  A4a:  $\text{dom}(x \cdot y) \cong \text{dom}((\text{dom } x) \cdot y)$  and
  A4b:  $\text{cod}(x \cdot y) \cong \text{cod}(x \cdot (\text{cod } y))$  and
  A5:  $x \cdot (y \cdot z) \cong (x \cdot y) \cdot z$ 
begin
lemma True nitpick [satisfy] oops — Consistency

lemma InconsistencyAutomatic:  $(\exists x. \neg(E x)) \rightarrow \text{False}$  by (metis A1 A2a A3a) — Inconsistency
lemma  $\forall x. E x$  using InconsistencyAutomatic by auto

lemma InconsistencyInteractive:
assumes NEx:  $\exists x. \neg(E x)$  shows False
proof —
obtain a where 1:  $\neg(E a)$  using NEx by auto
have 2:  $a \cdot (\text{dom } a) \cong a$  using A3a by blast
have 3:  $\neg(E(a \cdot (\text{dom } a)))$  using 1 2 by metis
have 4:  $E(a \cdot (\text{dom } a)) \leftrightarrow \text{dom } a \cong \text{cod}(\text{dom } a)$  using A1 by blast
have 5:  $\text{cod}(\text{dom } a) \cong \text{dom } a$  using A2a by blast
have 6:  $E(a \cdot (\text{dom } a)) \leftrightarrow \text{dom } a \cong \text{dom } a$  using 4 5 by auto
have 7:  $E(a \cdot (\text{dom } a))$  using 6 by blast
then show ?thesis using 7 3 by blast
qed
end

```

5.3 AxiomsSet7orig (technically flawed)

The axioms by Freyd and Scedrov in their original notation, without the suggested correction of axiom A1.

We present the constricted inconsistency argument from above once again, but this time in the original notation of Freyd and Scedrov.

```

locale AxiomsSet7orig =
fixes
  source::  $i \Rightarrow i$  ( $\square$ - [108] 109) and
  target::  $i \Rightarrow i$  ( $-\square$  [110] 111) and

```

compositionF:: $i \Rightarrow i \Rightarrow i$ (**infix** · 110)

assumes

A1: $E(x \cdot y) \leftrightarrow (x \square \cong \square y)$ **and**

A2a: $((\square x) \square) \cong \square x$ **and**

A2b: $\square(x \square) \cong \square x$ **and**

A3a: $(\square x) \cdot x \cong x$ **and**

A3b: $x \cdot (\square x) \cong x$ **and**

A4a: $\square(x \cdot y) \cong \square(x \cdot (\square y))$ **and**

A4b: $(x \cdot y) \square \cong ((x \square) \cdot y) \square$ **and**

A5: $x \cdot (y \cdot z) \cong (x \cdot y) \cdot z$

begin

lemma *True nitpick [satisfy] oops* — Consistency

lemma *InconsistencyAutomatic*: $(\exists x. \neg(E x)) \rightarrow \text{False}$ **by** (*metis A1 A2a A3a*) — Inconsistency

lemma $\forall x. E x$ **using** *InconsistencyAutomatic* **by** *auto*

lemma *InconsistencyInteractive*:

assumes *NEx*: $\exists x. \neg(E x)$ **shows** *False*

proof —

obtain *a* **where** *1*: $\neg(E a)$ **using** *assms* **by** *auto*

have *2*: $(\square a) \cdot a \cong a$ **using** *A3a* **by** *blast*

have *3*: $\neg(E((\square a) \cdot a))$ **using** *1 2* **by** *metis*

have *4*: $E((\square a) \cdot a) \leftrightarrow (\square a) \square \cong \square a$ **using** *A1* **by** *blast*

have *5*: $(\square a) \square \cong \square a$ **using** *A2a* **by** *blast*

have *6*: $E((\square a) \cdot a)$ **using** *4 5* **by** *blast*

then show *?thesis* **using** *6 3* **by** *blast*

qed

end

5.4 AxiomsSet8 (algebraic reading, still technically flawed)

The axioms by Freyd and Scedrov in our notation again, but this time we adopt an algebraic reading of the free variables, meaning that they range over existing morphisms only.

locale *AxiomsSet8* =

assumes

B1: $\forall x. \forall y. E(x \cdot y) \leftrightarrow \text{dom } x \cong \text{cod } y$ **and**

B2a: $\forall x. \text{cod}(\text{dom } x) \cong \text{dom } x$ **and**

B2b: $\forall y. \text{dom}(\text{cod } y) \cong \text{cod } y$ **and**

B3a: $\forall x. x \cdot (\text{dom } x) \cong x$ **and**

B3b: $\forall y. (\text{cod } y) \cdot y \cong y$ **and**

B4a: $\forall x. \forall y. \text{dom}(x \cdot y) \cong \text{dom}((\text{dom } x) \cdot y)$ **and**

B4b: $\forall x. \forall y. \text{cod}(x \cdot y) \cong \text{cod}(x \cdot (\text{cod } y))$ **and**

B5: $\forall x. \forall y. \forall z. x \cdot (y \cdot z) \cong (x \cdot y) \cdot z$

begin

lemma *True nitpick [satisfy] oops* — Consistency

lemma **assumes** $\exists x. \neg(E x)$ **shows** *True nitpick [satisfy] oops* — Consistency

lemma **assumes** $(\exists x. \neg(E x)) \wedge (\exists x. (E x))$ **shows** *True nitpick [satisfy] oops* — Consistency

end

None of the axioms in AxiomsSet5 are implied.

context *AxiomsSet8*

begin

lemma *S1*: $E(\text{dom } x) \rightarrow E x$ **nitpick oops** — Nitpick finds a countermodel

lemma *S2*: $E(\text{cod } y) \rightarrow E y$ **nitpick oops** — Nitpick finds a countermodel

lemma *S3*: $E(x \cdot y) \leftrightarrow \text{dom } x \cong \text{cod } y$ **nitpick oops** — Nitpick finds a countermodel

lemma *S4*: $x \cdot (y \cdot z) \cong (x \cdot y) \cdot z$ **nitpick oops** — Nitpick finds a countermodel

lemma *S5*: $(\text{cod } y) \cdot y \cong y$ **nitpick oops** — Nitpick finds a countermodel

lemma *S6*: $x \cdot (\text{dom } x) \cong x$ **nitpick oops** — Nitpick finds a countermodel

end

5.5 AxiomsSet8Strict (algebraic reading)

The situation changes when strictness conditions are postulated. Note that in the algebraic framework of Freyd and Scedrov such conditions have to be assumed as given in the logic, while here we can explicitly encode them as axioms.

```

locale AxiomsSet8Strict = AxiomsSet8 +
assumes
  B0a:  $E(x \cdot y) \rightarrow (E x \wedge E y)$  and
  B0b:  $E(\text{dom } x) \rightarrow E x$  and
  B0c:  $E(\text{cod } x) \rightarrow E x$ 
begin
  lemma True nitpick [satisfy] oops — Consistency
  lemma assumes  $\exists x. \neg(E x)$  shows True nitpick [satisfy] oops — Consistency
  lemma assumes  $(\exists x. \neg(E x)) \wedge (\exists x. (E x))$  shows True nitpick [satisfy] oops — Consistency
end

```

5.5.1 AxiomsSet8Strict entails AxiomsSet5

```

context AxiomsSet8Strict
begin
  lemma S1:  $E(\text{dom } x) \rightarrow E x$  using B0b by blast
  lemma S2:  $E(\text{cod } y) \rightarrow E y$  using B0c by blast
  lemma S3:  $E(x \cdot y) \leftrightarrow \text{dom } x \simeq \text{cod } y$  by (metis B0a B0b B0c B1 B3a)
  lemma S4:  $x \cdot (y \cdot z) \cong (x \cdot y) \cdot z$  by (meson B0a B5)
  lemma S5:  $(\text{cod } y) \cdot y \cong y$  using B0a B3b by blast
  lemma S6:  $x \cdot (\text{dom } x) \cong x$  using B0a B3a by blast
end

```

5.5.2 AxiomsSet5 entails AxiomsSet8Strict

```

context AxiomsSet5
begin
  lemma B0a:  $E(x \cdot y) \rightarrow (E x \wedge E y)$  using S1 S2 S3 by blast
  lemma B0b:  $E(\text{dom } x) \rightarrow E x$  using S1 by blast
  lemma B0c:  $E(\text{cod } x) \rightarrow E x$  using S2 by blast
  lemma B1:  $\forall x. \forall y. E(x \cdot y) \leftrightarrow \text{dom } x \cong \text{cod } y$  by (metis S3 S5)
  lemma B2a:  $\forall x. \text{cod}(\text{dom } x) \cong \text{dom } x$  using A2 by blast
  lemma B2b:  $\forall y. \text{dom}(\text{cod } y) \cong \text{cod } y$  using A2b by blast
  lemma B3a:  $\forall x. x \cdot (\text{dom } x) \cong x$  using S6 by blast
  lemma B3b:  $\forall y. (\text{cod } y) \cdot y \cong y$  using S5 by blast
  lemma B4a:  $\forall x. \forall y. \text{dom}(x \cdot y) \cong \text{dom}((\text{dom } x) \cdot y)$  by (metis S1 S3 S4 S6)
  lemma B4b:  $\forall x. \forall y. \text{cod}(x \cdot y) \cong \text{cod}(x \cdot (\text{cod } y))$  by (metis S1 S2 S3 S4 S5)
  lemma B5:  $\forall x. \forall y. \forall z. x \cdot (y \cdot z) \cong (x \cdot y) \cdot z$  using S4 by blast
end

```

5.5.3 AxiomsSet8Strict is Redundant

AxiomsSet8Strict is redundant: either the B2-axioms can be omitted or the B4-axioms.

```

context AxiomsSet8Strict
begin
  lemma B2aRedundant:  $\forall x. \text{cod}(\text{dom } x) \cong \text{dom } x$  by (metis B0a B1 B3a)
  lemma B2bRedundant:  $\forall y. \text{dom}(\text{cod } y) \cong \text{cod } y$  by (metis B0a B1 B3b)
  lemma B4aRedundant:  $\forall x. \forall y. \text{dom}(x \cdot y) \cong \text{dom}((\text{dom } x) \cdot y)$  by (metis B0a B0b B1 B3a B5)
  lemma B4bRedundant:  $\forall x. \forall y. \text{cod}(x \cdot y) \cong \text{cod}(x \cdot (\text{cod } y))$  by (metis B0a B0c B1 B3b B5)
end

```

6 The Axioms Sets of Mac Lane [5]

We analyse the axioms set suggested by Mac Lane [5] already in 1948. As for the theory by Freyd and Scedrov above, which was developed much later, we need to assume strictness of composition to show equivalence to our previous axiom sets. Note that his complicated conditions on existence of compositions proved to be unnecessary, as we show. It shows it is hard to think about partial operations.

```

locale AxiomsSetMcL =
assumes
   $C_0 : E(x \cdot y) \rightarrow (E x \wedge E y)$  and
   $C_1 : \forall \gamma \beta \alpha. (E(\gamma \cdot \beta) \wedge E((\gamma \cdot \beta) \cdot \alpha)) \rightarrow E(\beta \cdot \alpha)$  and
   $C_1' : \forall \gamma \beta \alpha. (E(\beta \cdot \alpha) \wedge E(\gamma \cdot (\beta \cdot \alpha))) \rightarrow E(\gamma \cdot \beta)$  and
   $C_2 : \forall \gamma \beta \alpha. (E(\gamma \cdot \beta) \wedge E(\beta \cdot \alpha)) \rightarrow (E((\gamma \cdot \beta) \cdot \alpha) \wedge E(\gamma \cdot (\beta \cdot \alpha)) \wedge ((\gamma \cdot \beta) \cdot \alpha) = (\gamma \cdot (\beta \cdot \alpha)))$  and
   $C_3 : \forall \gamma. \exists eD. \text{IDMcL}(eD) \wedge E(\gamma \cdot eD)$  and
   $C_4 : \forall \gamma. \exists eR. \text{IDMcL}(eR) \wedge E(eR \cdot \gamma)$ 
begin
  lemma True nitpick [satisfy] oops — Consistency
  lemma assumes  $\exists x. \neg(E x)$  shows True nitpick [satisfy] oops — Consistency
  lemma assumes  $(\exists x. \neg(E x)) \wedge (\exists x. (E x))$  shows True nitpick [satisfy] oops — Consistency
end

```

Remember that IDMcL was defined on p. 2 and proved equivalent to ID.

6.1 AxiomsSetMcL entails AxiomsSet1

```

context AxiomsSetMcL
begin
  lemma  $S_i : E(x \cdot y) \rightarrow (E x \wedge E y)$  using  $C_0$  by blast
  lemma  $E_i : E(x \cdot y) \leftarrow (E x \wedge E y \wedge (\exists z. z \cdot z \cong z \wedge x \cdot z \cong x \wedge z \cdot y \cong y))$  by (metis  $C_2$ )
  lemma  $A_i : x \cdot (y \cdot z) \cong (x \cdot y) \cdot z$  by (metis  $C_1 C_1' C_2 C_0$ )
  lemma  $C_i : \forall y. \exists i. \text{ID } i \wedge i \cdot y \cong y$  using  $C_4$  by fastforce
  lemma  $D_i : \forall x. \exists j. \text{ID } j \wedge x \cdot j \cong x$  using  $C_3$  by fastforce
end

```

6.2 AxiomsSet1 entails AxiomsSetMcL

```

context AxiomsSet1
begin
  lemma  $C_0 : E(x \cdot y) \rightarrow (E x \wedge E y)$  using  $S_i$  by blast
  lemma  $C_1 : \forall \gamma \beta \alpha. (E(\gamma \cdot \beta) \wedge E((\gamma \cdot \beta) \cdot \alpha)) \rightarrow E(\beta \cdot \alpha)$  by (metis  $A_i S_i$ )
  lemma  $C_1' : \forall \gamma \beta \alpha. (E(\beta \cdot \alpha) \wedge E(\gamma \cdot (\beta \cdot \alpha))) \rightarrow E(\gamma \cdot \beta)$  by (metis  $A_i S_i$ )
  lemma  $C_2 : \forall \gamma \beta \alpha. (E(\gamma \cdot \beta) \wedge E(\beta \cdot \alpha)) \rightarrow (E((\gamma \cdot \beta) \cdot \alpha) \wedge E(\gamma \cdot (\beta \cdot \alpha)) \wedge ((\gamma \cdot \beta) \cdot \alpha) = (\gamma \cdot (\beta \cdot \alpha)))$  by (smt  $A_i C_i E_i S_i$ )
  lemma  $C_3 : \forall \gamma. \exists eD. \text{IDMcL}(eD) \wedge E(\gamma \cdot eD)$  using  $D_i$  by force
  lemma  $C_4 : \forall \gamma. \exists eR. \text{IDMcL}(eR) \wedge E(eR \cdot \gamma)$  using  $C_i$  by force
end

```

6.3 Skolemization of the Axioms of Mac Lane

Mac Lane employs diagrammatic composition instead of the set-theoretic definition as used in our axiom sets. As we have seen above, this is not a problem as long as composition is the only primitive. But when adding the Skolem terms *dom* and *cod* care must be taken and we should actually transform all axioms into a common form. Below we address this (in a minimal way) by using *dom* in axiom C_3 s and *cod* in axiom C_4 s, which is opposite of what Mac Lane proposed. For this axioms set we then show equivalence to AxiomsSet1/2/5.

```

locale SkolemizedAxiomsSetMcL =
assumes
   $C_0s : (E(x \cdot y) \rightarrow (E x \wedge E y)) \wedge (E(\text{dom } x) \rightarrow E x) \wedge (E(\text{cod } y) \rightarrow E y)$  and

```

$C_1s : \forall \gamma \beta \alpha. (E(\gamma \cdot \beta) \wedge E((\gamma \cdot \beta) \cdot \alpha)) \rightarrow E(\beta \cdot \alpha)$ **and**
 $C_1's : \forall \gamma \beta \alpha. (E(\beta \cdot \alpha) \wedge E(\gamma \cdot (\beta \cdot \alpha))) \rightarrow E(\gamma \cdot \beta)$ **and**
 $C_2s : \forall \gamma \beta \alpha. (E(\gamma \cdot \beta) \wedge E(\beta \cdot \alpha)) \rightarrow (E((\gamma \cdot \beta) \cdot \alpha) \wedge E(\gamma \cdot (\beta \cdot \alpha)) \wedge ((\gamma \cdot \beta) \cdot \alpha) = (\gamma \cdot (\beta \cdot \alpha)))$ **and**
 $C_3s : \forall \gamma. \text{IDMcL}(\text{dom } \gamma) \wedge E(\gamma \cdot (\text{dom } \gamma))$ **and**
 $C_4s : \forall \gamma. \text{IDMcL}(\text{cod } \gamma) \wedge E((\text{cod } \gamma) \cdot \gamma)$
begin
lemma *True nitpick* [*satisfy*] **oops** — Consistency
lemma **assumes** $\exists x. \neg(E x)$ **shows** *True nitpick* [*satisfy*] **oops** — Consistency
lemma **assumes** $(\exists x. \neg(E x)) \wedge (\exists x. (E x))$ **shows** *True nitpick* [*satisfy*] **oops** — Consistency
end

6.4 SkolemizedAxiomsSetMcL entails AxiomsSetMcL and AxiomsSet1-5

context *SkolemizedAxiomsSetMcL*
begin
lemma $C_0 : E(x \cdot y) \rightarrow (E x \wedge E y)$ **using** C_0s **by** *blast*
lemma $C_1 : \forall \gamma \beta \alpha. (E(\gamma \cdot \beta) \wedge E((\gamma \cdot \beta) \cdot \alpha)) \rightarrow E(\beta \cdot \alpha)$ **using** C_1s **by** *blast*
lemma $C_1' : \forall \gamma \beta \alpha. (E(\beta \cdot \alpha) \wedge E(\gamma \cdot (\beta \cdot \alpha))) \rightarrow E(\gamma \cdot \beta)$ **using** $C_1's$ **by** *blast*
lemma $C_2 : \forall \gamma \beta \alpha. (E(\gamma \cdot \beta) \wedge E(\beta \cdot \alpha)) \rightarrow (E((\gamma \cdot \beta) \cdot \alpha) \wedge E(\gamma \cdot (\beta \cdot \alpha)) \wedge ((\gamma \cdot \beta) \cdot \alpha) = (\gamma \cdot (\beta \cdot \alpha)))$ **using** C_2s
by *blast*
lemma $C_3 : \forall \gamma. \exists eD. \text{IDMcL}(eD) \wedge E(\gamma \cdot eD)$ **by** (*metis* C_0s C_3s)
lemma $C_4 : \forall \gamma. \exists eR. \text{IDMcL}(eR) \wedge E(eR \cdot \gamma)$ **by** (*metis* C_0s C_4s)

lemma $S_i : E(x \cdot y) \rightarrow (E x \wedge E y)$ **using** C_0s **by** *blast*
lemma $E_i : E(x \cdot y) \leftarrow (E x \wedge E y \wedge (\exists z. z \cdot z \cong z \wedge x \cdot z \cong x \wedge z \cdot y \cong y))$ **by** (*metis* C_2s)
lemma $A_i : x \cdot (y \cdot z) \cong (x \cdot y) \cdot z$ **by** (*metis* C_1s $C_1's$ C_2s C_0s)
lemma $C_i : \forall y. \exists i. \text{ID } i \wedge i \cdot y \cong y$ **by** (*metis* C_0s C_4s)
lemma $D_i : \forall x. \exists j. \text{ID } j \wedge x \cdot j \cong x$ **by** (*metis* C_0s C_3s)

lemma $S_{ii} : (E(x \cdot y) \rightarrow (E x \wedge E y)) \wedge (E(\text{dom } x) \rightarrow E x) \wedge (E(\text{cod } y) \rightarrow E y)$ **using** C_0s **by** *blast*
lemma $E_{ii} : E(x \cdot y) \leftarrow (E x \wedge E y \wedge (\exists z. z \cdot z \cong z \wedge x \cdot z \cong x \wedge z \cdot y \cong y))$ **by** (*metis* C_2s)
lemma $A_{ii} : x \cdot (y \cdot z) \cong (x \cdot y) \cdot z$ **by** (*metis* C_1s $C_1's$ C_2s C_0s)
lemma $C_{ii} : E y \rightarrow (\text{ID}(\text{cod } y) \wedge (\text{cod } y) \cdot y \cong y)$ **using** C_4s **by** *auto*
lemma $D_{ii} : E x \rightarrow (\text{ID}(\text{dom } x) \wedge x \cdot (\text{dom } x) \cong x)$ **using** C_3s **by** *auto*

— AxiomsSets3/4 are omitted here; we already know they are equivalent.

lemma $S1 : E(\text{dom } x) \rightarrow E x$ **using** C_0s **by** *blast*
lemma $S2 : E(\text{cod } y) \rightarrow E y$ **using** C_0s **by** *blast*
lemma $S3 : E(x \cdot y) \leftrightarrow \text{dom } x \cong \text{cod } y$ **by** (*metis* (*full-types*) C_0s C_1s $C_1's$ C_2s C_3s C_4s)
lemma $S4 : x \cdot (y \cdot z) \cong (x \cdot y) \cdot z$ **by** (*metis* C_0s C_1s $C_1's$ C_2s)
lemma $S5 : (\text{cod } y) \cdot y \cong y$ **using** C_0s C_4s **by** *blast*
lemma $S6 : x \cdot (\text{dom } x) \cong x$ **using** C_0s C_3s **by** *blast*
end

References

- [1] C. Benzmüller and D. Scott. Automating free logic in Isabelle/HOL. In G.-M. Greuel, T. Koch, P. Paule, and A. Sommese, editors, *Mathematical Software – ICMS 2016, 5th International Congress, Proceedings*, volume 9725 of *LNCSE*, pages 43–50, Berlin, Germany, 2016. Springer.
- [2] C. Benzmüller and D. Scott. Some reflections on a computer-aided theory exploration study in category theory (extended abstract). In T. C. Hales, C. Kaliszyk, S. Schulz, and J. Urban, editors, *3rd Conference on Artificial Intelligence and Theorem Proving (AITP 2018), Book of Abstracts*, 2018.

- [3] C. Benzmüller and D. S. Scott. Axiomatizing category theory in free logic. Technical report, CoRR, 2016. <http://arxiv.org/abs/1609.01493>.
- [4] P. J. Freyd and A. Scedrov. *Categories, Allegories*. North Holland, 1990.
- [5] S. McLane. Groups, categories and duality. *Proceedings of the National Academy of Sciences*, 34(6):263–267, 1948.
- [6] D. Scott. Identity and existence in intuitionistic logic. In M. Fourman, C. Mulvey, and D. Scott, editors, *Applications of Sheaves: Proceedings of the Research Symposium on Applications of Sheaf Theory to Logic, Algebra, and Analysis, Durham, July 9–21, 1977*, volume 752 of *Lecture Notes in Mathematics*, pages 660–696. Springer Berlin Heidelberg, 1979.