

# Strict Omega Categories

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## Abstract

This theory formalises a definition of strict  $\omega$ -categories and the strict  $\omega$ -category of pasting diagrams, following [1]. It is the first step towards a formalisation of weak infinity categories à la Batanin–Leinster.

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theory <i>Globular-Set</i>		

imports *HOL-Library.FuncSet*

begin

## 1 Background material on extensional functions

lemma *PiE-imp-Pi*:  $f \in A \rightarrow_E B \implies f \in A \rightarrow B$  by *fast*

lemma *PiE-iff'*:  $f \in A \rightarrow_E B = (f \in A \rightarrow B \wedge f \in \text{extensional } A)$   
by (*simp add: PiE-iff Pi-iff*)

**abbreviation** *composing* ( $\langle - \circ - \downarrow - \rangle$  [60,0,60]59)

where  $g \circ f \downarrow D \equiv \text{compose } D \ g \ f$

**lemma** *compose-PiE*:  $f \in A \rightarrow B \implies g \in B \rightarrow C \implies g \circ f \downarrow A \in A \rightarrow_E C$   
by (*metis funcset-compose compose-extensional PiE-iff'*)

**lemma** *compose-eq-iff*:  $(g \circ f \downarrow A = k \circ h \downarrow A) = (\forall x \in A. g (f x) = k (h x))$   
**proof** (*safe*)

**fix**  $x$  **assume**  $g \circ f \downarrow A = k \circ h \downarrow A \ x \in A$

**then show**  $g (f x) = k (h x)$  **by** (*metis compose-eq*)

**next**

**assume**  $\forall x \in A. g (f x) = k (h x)$

**hence**  $\bigwedge x. x \in A \implies (g \circ f \downarrow A) x = (k \circ h \downarrow A) x$  **by** (*metis compose-eq*)

**then show**  $g \circ f \downarrow A = k \circ h \downarrow A$  **by** (*metis extensionalityI compose-extensional*)

**qed**

**lemma** *compose-eq-if*:  $(\bigwedge x. x \in A \implies g (f x) = k (h x)) \implies g \circ f \downarrow A = k \circ h \downarrow A$

**using** *compose-eq-iff* **by** *blast*

**lemma** *compose-compose-eq-iff2*:  $(h \circ (g \circ f \downarrow A) \downarrow A = h' \circ (g' \circ f' \downarrow A) \downarrow A) =$   
 $(\forall x \in A. h (g (f x)) = h' (g' (f' x)))$

**by** (*simp add: compose-eq compose-eq-iff*)

**lemma** *compose-compose-eq-iff1*: **assumes**  $f \in A \rightarrow B \ f' \in A \rightarrow B$

**shows**  $((h \circ g \downarrow B) \circ f \downarrow A = (h' \circ g' \downarrow B) \circ f' \downarrow A) = (\forall x \in A. h (g (f x)) = h' (g' (f' x)))$

**proof** –

**have**  $(h \circ g \downarrow B) \circ f \downarrow A = h \circ (g \circ f \downarrow A) \downarrow A$  **by** (*metis assms(1) compose-assoc*)

**moreover have**  $(h' \circ g' \downarrow B) \circ f' \downarrow A = h' \circ (g' \circ f' \downarrow A) \downarrow A$  **by** (*metis assms(2) compose-assoc*)

**ultimately have**  $h: ((h \circ g \downarrow B) \circ f \downarrow A = (h' \circ g' \downarrow B) \circ f' \downarrow A) =$

$(h \circ (g \circ f \downarrow A) \downarrow A = h' \circ (g' \circ f' \downarrow A) \downarrow A)$  **by** *presburger*

**then show** *?thesis* **by** (*simp only: h compose-compose-eq-iff2*)

**qed**

**lemma** *compose-compose-eq-iff1*:  $\llbracket f \in A \rightarrow B; f' \in A \rightarrow B; \forall x \in A. h (g (f x)) = h' (g' (f' x)) \rrbracket \implies$

$(h \circ g \downarrow B) \circ f \downarrow A = (h' \circ g' \downarrow B) \circ f' \downarrow A$

**using** *compose-compose-eq-iff1* **by** *blast*

**lemma** *compose-compose-eq-iff2*:  $\forall x \in A. h (g (f x)) = h' (g' (f' x)) \implies$

$h \circ (g \circ f \downarrow A) \downarrow A = h' \circ (g' \circ f' \downarrow A) \downarrow A$

**using** *compose-compose-eq-iff2* **by** *blast*

**lemma** *compose-restrict-eq1*:  $f \in A \rightarrow B \implies \text{restrict } g \ B \circ f \downarrow A = g \circ f \downarrow A$

**by** (*smt (verit) PiE compose-eq-iff restrict-apply'*)

**lemma** *compose-restrict-eq2*:  $g \circ (\text{restrict } f \ A) \downarrow A = g \circ f \downarrow A$

by (metis (mono-tags, lifting) compose-eq-if restrict-apply')

**lemma** *compose-Id-eq-restrict*:  $g \circ (\lambda x \in A. x) \downarrow A = \text{restrict } g \ A$   
 by (smt (verit) compose-restrict-eq1 compose-def restrict-apply' restrict-ext)

## 2 Globular sets

### 2.1 Globular sets

We define a locale *globular-set* that encodes the cell data of a strict  $\omega$ -category [1, Def 1.4.5]. The elements of  $X \ n$  are the  $n$ -cells, and the maps  $s$  and  $t$  give the source and target of a cell, respectively.

**locale** *globular-set* =  
 fixes  $X :: \text{nat} \Rightarrow 'a \ \text{set}$  and  $s :: \text{nat} \Rightarrow 'a \Rightarrow 'a$  and  $t :: \text{nat} \Rightarrow 'a \Rightarrow 'a$   
 assumes *s-fun*:  $s \ n \in X \ (\text{Suc } n) \rightarrow X \ n$   
 and *t-fun*:  $t \ n \in X \ (\text{Suc } n) \rightarrow X \ n$   
 and *s-comp*:  $x \in X \ (\text{Suc } (\text{Suc } n)) \implies s \ n \ (t \ (\text{Suc } n) \ x) = s \ n \ (s \ (\text{Suc } n) \ x)$   
 and *t-comp*:  $x \in X \ (\text{Suc } (\text{Suc } n)) \implies t \ n \ (s \ (\text{Suc } n) \ x) = t \ n \ (t \ (\text{Suc } n) \ x)$   
**begin**

**lemma** *s-comp'*:  $s \ n \circ t \ (\text{Suc } n) \downarrow X \ (\text{Suc } (\text{Suc } n)) = s \ n \circ s \ (\text{Suc } n) \downarrow X \ (\text{Suc } (\text{Suc } n))$

by (metis (full-types) compose-eq-if s-comp)

**lemma** *t-comp'*:  $t \ n \circ s \ (\text{Suc } n) \downarrow X \ (\text{Suc } (\text{Suc } n)) = t \ n \circ t \ (\text{Suc } n) \downarrow X \ (\text{Suc } (\text{Suc } n))$

by (metis (full-types) compose-eq-if t-comp)

These are the generalised source and target maps. The arguments are the dimension of the input and output, respectively. They allow notation similar to  $s^{m-p}$  in [1].

**fun**  $s' :: \text{nat} \Rightarrow \text{nat} \Rightarrow 'a \Rightarrow 'a$  **where**  
 $s' \ 0 \ 0 = \text{id}$  |  
 $s' \ 0 \ (\text{Suc } n) = \text{undefined}$  |  
 $s' \ (\text{Suc } m) \ n = (\text{if } \text{Suc } m < n \text{ then } \text{undefined}$   
   else if  $\text{Suc } m = n$  then  $\text{id}$   
   else  $s' \ m \ n \circ s \ m)$

**fun**  $t' :: \text{nat} \Rightarrow \text{nat} \Rightarrow 'a \Rightarrow 'a$  **where**  
 $t' \ 0 \ 0 = \text{id}$  |  
 $t' \ 0 \ (\text{Suc } n) = \text{undefined}$  |  
 $t' \ (\text{Suc } m) \ n = (\text{if } \text{Suc } m < n \text{ then } \text{undefined}$   
   else if  $\text{Suc } m = n$  then  $\text{id}$   
   else  $t' \ m \ n \circ t \ m)$

**lemma** *s'-n-n [simp]*:  $s' \ n \ n = \text{id}$   
 by (cases n, simp-all)

**lemma**  $s'$ -Suc-n-n [simp]:  $s' (Suc\ n)\ n = s\ n$   
**by** *simp*

**lemma**  $s'$ -Suc-Suc-n-n [simp]:  $s' (Suc\ (Suc\ n))\ n = s\ n \circ s\ (Suc\ n)$   
**by** *simp*

**lemma**  $s'$ -Suc [simp]:  $n \leq m \implies s' (Suc\ m)\ n = s'\ m\ n \circ s\ m$   
**by** *simp*

**lemma**  $s'$ -Suc':  $n < m \implies s'\ m\ n = s\ n \circ s'\ m\ (Suc\ n)$

**proof** (*induction m arbitrary: n*)

**case** 0

**then show** ?case **by** *blast*

**next**

**case** (Suc m)

**hence**  $n \leq m$  **by** *fastforce*

**show** ?case **proof** (*cases n = m, simp*)

**assume**  $n \neq m$

**then show**  $s' (Suc\ m)\ n = s\ n \circ s' (Suc\ m)\ (Suc\ n)$  **using** *Suc* **by** *fastforce*

**qed**

**qed**

**lemma**  $t'$ -n-n [simp]:  $t'\ n\ n = id$   
**by** (*cases n, simp-all*)

**lemma**  $t'$ -Suc-n-n [simp]:  $t' (Suc\ n)\ n = t\ n$   
**by** *simp*

**lemma**  $t'$ -Suc-Suc-n-n [simp]:  $t' (Suc\ (Suc\ n))\ n = t\ n \circ t\ (Suc\ n)$   
**by** *simp*

**lemma**  $t'$ -Suc [simp]:  $n \leq m \implies t' (Suc\ m)\ n = t'\ m\ n \circ t\ m$   
**by** *simp*

**lemma**  $t'$ -Suc':  $n < m \implies t'\ m\ n = t\ n \circ t'\ m\ (Suc\ n)$

**proof** (*induction m arbitrary: n*)

**case** 0

**then show** ?case **by** *blast*

**next**

**case** (Suc m)

**hence**  $n \leq m$  **by** *fastforce*

**show** ?case **proof** (*cases n = m, simp*)

**assume**  $n \neq m$

**then show**  $t' (Suc\ m)\ n = t\ n \circ t' (Suc\ m)\ (Suc\ n)$  **using** *Suc* **by** *fastforce*

**qed**

**qed**

**lemma**  $s'$ -fun:  $n \leq m \implies s'\ m\ n \in X\ m \rightarrow X\ n$   
**proof** (*induction m arbitrary: n*)

```

case 0
thus ?case by force
next
case (Suc m)
thus ?case proof (cases n = Suc m)
  case True
  then show ?thesis by auto
next
case False
hence  $n \leq m$  using  $\langle n \leq \text{Suc } m \rangle$  by force
thus ?thesis using Suc.IH s-fun s'-Suc by auto
qed
qed

```

**lemma**  $t'$ -fun:  $n \leq m \implies t' m n \in X m \rightarrow X n$

**proof** (induction m arbitrary: n)

```

case 0
thus ?case by force
next
case (Suc m)
thus ?case proof (cases n = Suc m)
  case True
  then show ?thesis by auto
next
case False
hence  $n \leq m$  using  $\langle n \leq \text{Suc } m \rangle$  by force
thus ?thesis using Suc.IH t-fun t'-Suc by auto
qed
qed

```

**lemma**  $s'$ -comp:  $\llbracket n < m; x \in X m \rrbracket \implies s n (t' m (\text{Suc } n) x) = s' m n x$

**proof** (induction m - n arbitrary: n)

```

case 0
then show ?case by force
next
case IH: (Suc k)
show ?case proof (cases k)
  case 0
  with IH(2) have  $m = \text{Suc } n$  by fastforce
  then show ?thesis using s'-Suc' by auto
next
case (Suc k')
with  $\langle \text{Suc } k = m - n \rangle$  have hle:  $\text{Suc } (\text{Suc } n) \leq m$  by simp
hence  $\text{Suc } n < m$  by force
hence  $\text{Suc } (\text{Suc } n) \leq m$  by fastforce
have  $s n (t' m (\text{Suc } n) x)$ 
=  $s n (t (\text{Suc } n) (t' m (\text{Suc } (\text{Suc } n)) x))$  using t'-Suc'  $\langle \text{Suc } n < m \rangle$  by simp
also have ... =  $s n (s (\text{Suc } n) (t' m (\text{Suc } (\text{Suc } n)) x))$ 
using t'-fun  $\langle \text{Suc } (\text{Suc } n) \leq m \rangle$  s-comp IH(4) by blast

```

```

    also have ... = s n (s' m (Suc n) x)
      using IH Suc-diff-Suc Suc-inject ⟨Suc n < m⟩ by presburger
    finally show ?thesis using ⟨n < m⟩ s'-Suc' by simp
  qed
qed

lemma t'-comp: [ n < m; x ∈ X m ] ⇒ t n (s' m (Suc n) x) = t' m n x
proof (induction m - n arbitrary: n)
  case 0
  then show ?case by force
next
  case IH: (Suc k)
  show ?case proof (cases k)
    case 0
    with IH(2) have m = Suc n by fastforce
    then show ?thesis using IH.prem1 by auto
  next
    case (Suc k')
    with ⟨Suc k = m - n⟩ have hle: Suc (Suc n) ≤ m by simp
    hence Suc n < m by force
    hence Suc (Suc n) ≤ m by fastforce
    have t n (s' m (Suc n) x)
      = t n (s (Suc n) (s' m (Suc (Suc n)) x)) using s'-Suc' ⟨Suc n < m⟩ by simp
    also have ... = t n (t (Suc n) (s' m (Suc (Suc n)) x))
      using s'-fun ⟨Suc (Suc n) ≤ m⟩ t-comp IH(4) by blast
    also have ... = t n (t' m (Suc n) x)
      using IH Suc-diff-Suc Suc-inject ⟨Suc n < m⟩ by presburger
    finally show ?thesis using ⟨n < m⟩ t'-Suc' by simp
  qed
qed

```

The following predicates and sets are needed to define composition in an  $\omega$ -category.

**definition** *is-parallel-pair* ::  $\text{nat} \Rightarrow \text{nat} \Rightarrow 'a \Rightarrow 'a \Rightarrow \text{bool}$  **where**  
*is-parallel-pair* m n x y  $\equiv n \leq m \wedge x \in X m \wedge y \in X m \wedge s' m n x = s' m n y \wedge t' m n x = t' m n y$

[1, p. 44]

**definition** *is-composable-pair* ::  $\text{nat} \Rightarrow \text{nat} \Rightarrow 'a \Rightarrow 'a \Rightarrow \text{bool}$  **where**  
*is-composable-pair* m n y x  $\equiv n < m \wedge y \in X m \wedge x \in X m \wedge t' m n x = s' m n y$

**definition** *composable-pairs* ::  $\text{nat} \Rightarrow \text{nat} \Rightarrow ('a \times 'a)$  set **where**  
*composable-pairs* m n =  $\{(y, x). \text{is-composable-pair } m n y x\}$

**lemma** *composable-pairs-empty*:  $m \leq n \implies \text{composable-pairs } m n = \{\}$   
 using *is-composable-pair-def composable-pairs-def* by simp

end

## 2.2 Maps between globular sets

We define maps between globular sets to be natural transformations of the corresponding functors [1, Def 1.4.5].

**locale** *globular-map* = *source: globular-set*  $X$   $s_X$   $t_X$  + *target: globular-set*  $Y$   $s_Y$   $t_Y$   
**for**  $X$   $s_X$   $t_X$   $Y$   $s_Y$   $t_Y$  +  
**fixes**  $\varphi :: \text{nat} \Rightarrow 'a \Rightarrow 'b$   
**assumes** *map-fun*:  $\varphi \ m \in X \ m \rightarrow Y \ m$   
**and** *is-natural-wrt-s*:  $x \in X \ (Suc \ m) \Longrightarrow \varphi \ m \ (s_X \ m \ x) = s_Y \ m \ (\varphi \ (Suc \ m) \ x)$   
**and** *is-natural-wrt-t*:  $x \in X \ (Suc \ m) \Longrightarrow \varphi \ m \ (t_X \ m \ x) = t_Y \ m \ (\varphi \ (Suc \ m) \ x)$   
**begin**

**lemma** *is-natural-wrt-s'*:  $\llbracket n \leq m; x \in X \ m \rrbracket \Longrightarrow \varphi \ n \ (source.s' \ m \ n \ x) = target.s' \ m \ n \ (\varphi \ m \ x)$

**proof** (*induction*  $m - n$  *arbitrary: n*)

**case**  $0$

**hence**  $m = n$  **by** *simp*

**then show** *?case* **by** *fastforce*

**next**

**case** (*Suc*  $k$ )

**hence**  $n < m$  **by** *force*

**hence** *Suc*  $n \leq m$  **by** *auto*

**have**  $\varphi \ n \ (source.s' \ m \ n \ x) = \varphi \ n \ (s_X \ n \ (source.s' \ m \ (Suc \ n) \ x))$

**using** *source.s'-Suc' <n < m>* **by** *simp*

**also have**  $\dots = s_Y \ n \ (\varphi \ (Suc \ n) \ (source.s' \ m \ (Suc \ n) \ x))$

**using** *source.s'-fun <Suc n ≤ m> Suc(1) Suc(4) is-natural-wrt-s* **by** *blast*

**also have**  $\dots = s_Y \ n \ (target.s' \ m \ (Suc \ n) \ (\varphi \ m \ x))$

**using** *Suc <Suc n ≤ m> Suc-diff-Suc Suc-inject <n < m>* **by** *presburger*

**finally show** *?case* **using** *target.s'-Suc' <n < m>* **by** *simp*

**qed**

**lemma** *is-natural-wrt-t'*:  $\llbracket n \leq m; x \in X \ m \rrbracket \Longrightarrow \varphi \ n \ (source.t' \ m \ n \ x) = target.t' \ m \ n \ (\varphi \ m \ x)$

**proof** (*induction*  $m - n$  *arbitrary: n*)

**case**  $0$

**hence**  $m = n$  **by** *simp*

**then show** *?case* **by** *fastforce*

**next**

**case** (*Suc*  $k$ )

**hence**  $n < m$  **by** *force*

**hence** *Suc*  $n \leq m$  **by** *auto*

**have**  $\varphi \ n \ (source.t' \ m \ n \ x) = \varphi \ n \ (t_X \ n \ (source.t' \ m \ (Suc \ n) \ x))$

**using** *source.t'-Suc' <n < m>* **by** *simp*

**also have**  $\dots = t_Y \ n \ (\varphi \ (Suc \ n) \ (source.t' \ m \ (Suc \ n) \ x))$

**using** *source.t'-fun <Suc n ≤ m> Suc(1) Suc(4) is-natural-wrt-t* **by** *blast*

**also have**  $\dots = t_Y \ n \ (target.t' \ m \ (Suc \ n) \ (\varphi \ m \ x))$

**using** *Suc <Suc n ≤ m> Suc-diff-Suc Suc-inject <n < m>* **by** *presburger*

**finally show** *?case using target.t'-Suc' <n < m> by simp*  
**qed**

**end**

The composition of two globular maps is itself a globular map. This intermediate locale gathers the data needed for such a statement.

**locale** *two-globular-maps = fst: globular-map X s<sub>X</sub> t<sub>X</sub> Y s<sub>Y</sub> t<sub>Y</sub> φ + snd: globular-map Y s<sub>Y</sub> t<sub>Y</sub> Z s<sub>Z</sub> t<sub>Z</sub> ψ*

**for** *X s<sub>X</sub> t<sub>X</sub> Y s<sub>Y</sub> t<sub>Y</sub> Z s<sub>Z</sub> t<sub>Z</sub> φ ψ*

**sublocale** *two-globular-maps ⊆ comp: globular-map X s<sub>X</sub> t<sub>X</sub> Z s<sub>Z</sub> t<sub>Z</sub> λm. ψ m ∘ φ m*

**proof** (*unfold-locales*)

**fix** *m*

**show** *ψ m ∘ φ m ∈ X m → Z m using fst.map-fun snd.map-fun by fastforce*

**next**

**fix** *x m assume x ∈ X (Suc m)*

**then show** *(ψ m ∘ φ m) (s<sub>X</sub> m x) = s<sub>Z</sub> m ((ψ (Suc m) ∘ φ (Suc m)) x)*

**using** *fst.is-natural-wrt-s snd.is-natural-wrt-s comp-apply fst.map-fun by fastforce*

**next**

**fix** *x m assume x ∈ X (Suc m)*

**then show** *(ψ m ∘ φ m) (t<sub>X</sub> m x) = t<sub>Z</sub> m ((ψ (Suc m) ∘ φ (Suc m)) x)*

**using** *fst.is-natural-wrt-t snd.is-natural-wrt-t comp-apply fst.map-fun by fastforce*

**qed**

**sublocale** *two-globular-maps ⊆ compose: globular-map X s<sub>X</sub> t<sub>X</sub> Z s<sub>Z</sub> t<sub>Z</sub> λm. ψ m ∘ φ m ↓ X m*

**proof** (*unfold-locales*)

**fix** *m*

**show** *ψ m ∘ φ m ↓ X m ∈ X m → Z m using funcset-compose fst.map-fun snd.map-fun by fast*

**next**

**fix** *x m assume x ∈ X (Suc m)*

**then show** *(ψ m ∘ φ m ↓ X m) (s<sub>X</sub> m x) = s<sub>Z</sub> m ((ψ (Suc m) ∘ φ (Suc m)) ↓ X (Suc m)) x)*

**by** (*metis PiE fst.is-natural-wrt-s snd.is-natural-wrt-s fst.map-fun compose-eq fst.source.s-fun*)

**next**

**fix** *x m assume x ∈ X (Suc m)*

**then show** *(ψ m ∘ φ m ↓ X m) (t<sub>X</sub> m x) = t<sub>Z</sub> m ((ψ (Suc m) ∘ φ (Suc m)) ↓ X (Suc m)) x)*

**by** (*metis PiE fst.is-natural-wrt-t snd.is-natural-wrt-t fst.map-fun compose-eq fst.source.t-fun*)

**qed**

### 2.3 The terminal globular set

The terminal globular set, with a unique  $m$ -cell for each  $m$  [1, p. 264].

**interpretation** *final-glob: globular-set*  $\lambda m. \{()\}$   $\lambda m. id$   $\lambda m. id$   
**by** (*unfold-locales, auto*)

**context** *globular-set*

**begin**

[1, p. 272]

**interpretation** *map-to-final-glob: globular-map*  $X\ s\ t$

$\lambda m. \{()\}$   $\lambda m. id$   $\lambda m. id$

$\lambda m. (\lambda x. ())$

**by** (*unfold-locales, simp-all*)

**end**

**end**

**theory** *Strict-Omega-Category*

**imports** *Globular-Set*

**begin**

### 3 Strict $\omega$ -categories

First, we define a locale *pre-strict-omega-category* that holds the data of a strict  $\omega$ -category without the associativity, unity and exchange axioms [1, Def 1.4.8 (a) - (b)]. We do this in order to set up convenient notation before we state the remaining axioms.

**locale** *pre-strict-omega-category* = *globular-set* +

**fixes** *comp* ::  $nat \Rightarrow nat \Rightarrow 'a \Rightarrow 'a \Rightarrow 'a$

**and** *i* ::  $nat \Rightarrow 'a \Rightarrow 'a$

**assumes** *comp-fun*: *is-composable-pair*  $m\ n\ x'\ x \Longrightarrow comp\ m\ n\ x'\ x \in X\ m$

**and** *i-fun*:  $i\ n \in X\ n \rightarrow X\ (Suc\ n)$

**and** *s-comp-Suc*: *is-composable-pair*  $(Suc\ m)\ m\ x'\ x \Longrightarrow s\ m\ (comp\ (Suc\ m)\ m\ x'\ x) = s\ m\ x$

**and** *t-comp-Suc*: *is-composable-pair*  $(Suc\ m)\ m\ x'\ x \Longrightarrow t\ m\ (comp\ (Suc\ m)\ m\ x'\ x) = t\ m\ x'$

**and** *s-comp*:  $\llbracket is-composable-pair\ (Suc\ m)\ n\ x'\ x; n < m \rrbracket \Longrightarrow s\ m\ (comp\ (Suc\ m)\ n\ x'\ x) = comp\ m\ n\ (s\ m\ x')\ (s\ m\ x)$

**and** *t-comp*:  $\llbracket is-composable-pair\ (Suc\ m)\ n\ x'\ x; n < m \rrbracket \Longrightarrow t\ m\ (comp\ (Suc\ m)\ n\ x'\ x) = comp\ m\ n\ (t\ m\ x')\ (s\ m\ x)$

**and** *s-i*:  $x \in X\ n \Longrightarrow s\ n\ (i\ n\ x) = x$

**and** *t-i*:  $x \in X\ n \Longrightarrow t\ n\ (i\ n\ x) = x$

**begin**

Similar to the generalised source and target maps in *globular-set*, we defined a generalised identity map. The first argument gives the dimension

of the resulting identity cell, while the second gives the dimension of the input cell.

```

fun  $i'$  ::  $nat \Rightarrow nat \Rightarrow 'a \Rightarrow 'a$  where
 $i' 0 0 = id$  |
 $i' 0 (Suc n) = undefined$  |
 $i' (Suc m) n = (if Suc m < n then undefined$ 
   $else if Suc m = n then id$ 
   $else i m \circ i' m n)$ 

```

```

lemma  $i'-n-n$  [simp]:  $i' n n = id$ 
by (metis  $i'.elims$   $i'.simps(1)$  less-irrefl-nat)

```

```

lemma  $i'-Suc-n-n$  [simp]:  $i' (Suc n) n = i n$ 
by simp

```

```

lemma  $i'-Suc$  [simp]:  $n \leq m \Longrightarrow i' (Suc m) n = i m \circ i' m n$ 
by fastforce

```

```

lemma  $i'-Suc'$ :  $n < m \Longrightarrow i' m n = i' m (Suc n) \circ i n$ 

```

```

proof (induction  $m$  arbitrary:  $n$ )

```

```

  case 0

```

```

    then show ?case by blast

```

```

next

```

```

  case ( $Suc m$ )

```

```

    then show ?case by force

```

```

qed

```

```

lemma  $i'-fun$ :  $n \leq m \Longrightarrow i' m n \in X n \rightarrow X m$ 

```

```

proof (induction  $m$  arbitrary:  $n$ )

```

```

  case 0

```

```

    then show ?case by fastforce

```

```

next

```

```

  case ( $Suc m$ )

```

```

    thus ?case proof (cases  $n = Suc m$ )

```

```

      case True

```

```

        then show ?thesis by auto

```

```

    next

```

```

      case False

```

```

        hence  $n \leq m$  using  $\langle n \leq Suc m \rangle$  by force

```

```

        thus ?thesis using Suc.IH  $i'-fun$  by auto

```

```

    qed

```

```

qed

```

```

end

```

Now we may define a strict  $\omega$ -category including the composition, unity and exchange axioms [1, Def 1.4.8 (c) - (f)].

```

locale strict-omega-category = pre-strict-omega-category +

```

```

  assumes comp-assoc:  $\llbracket is-composable-pair\ m\ n\ x'\ x; is-composable-pair\ m\ n\ x''$ 

```

```

x']  $\implies$ 
  comp m n (comp m n x'' x') x = comp m n x'' (comp m n x' x)
and i-comp:  $\llbracket n < m; x \in X m \rrbracket \implies$  comp m n (i' m n (t' m n x)) x = x
and comp-i:  $\llbracket n < m; x \in X m \rrbracket \implies$  comp m n x (i' m n (s' m n x)) = x
and bin-interchange:  $\llbracket q < p; p < m;
  is-composable-pair m p y' y; is-composable-pair m p x' x;
  is-composable-pair m q y' x'; is-composable-pair m q y x \rrbracket \implies$ 
  comp m q (comp m p y' y) (comp m p x' x) = comp m p (comp m q y' x')
(comp m q y x)
and null-interchange:  $\llbracket q < p; is-composable-pair p q x' x \rrbracket \implies$ 
  comp (Suc p) q (i p x') (i p x) = i p (comp p q x' x)

```

```

locale strict-omega-functor = globular-map +
  source: strict-omega-category X s_X t_X comp_X i_X +
  target: strict-omega-category Y s_Y t_Y comp_Y i_Y
for comp_X i_X comp_Y i_Y +
assumes commute-with-comp: is-composable-pair m n x' x  $\implies$ 
   $\varphi m$  (comp_X m n x' x) = comp_Y m n ( $\varphi m$  x') ( $\varphi m$  x)
and commute-with-id:  $x \in X n \implies \varphi$  (Suc n) (i_X n x) = i_Y n ( $\varphi n$  x)

```

```

end
theory Pasting-Diagram
imports Strict-Omega-Category

```

```

begin

```

## 4 The category of pasting diagrams

We define the strict  $\omega$ -category of pasting diagrams, 'pd'. We encode its cells as rooted trees. First we develop some basic theory of trees.

### 4.1 Rooted trees

```

datatype tree = Node (subtrees: tree list) — [1, p. 268]

```

```

abbreviation Leaf :: tree where

```

```

Leaf  $\equiv$  Node []

```

```

fun subtree :: tree  $\Rightarrow$  nat list  $\Rightarrow$  tree ( $\langle \cdot \rangle$  !t  $\rightarrow$  [59,60]59) where

```

```

t !t [] = t |

```

```

t !t (i#xs) = subtrees (t !t xs) ! i

```

```

value Leaf !t []

```

```

value Node [Node [Leaf, Leaf, Leaf], Leaf, Node [Leaf]] !t [0]

```

```

value Node [Node [Leaf, Leaf, Leaf], Leaf, Node [Leaf]] !t [2,0]

```

```

value Node [Node [Leaf, Leaf, Leaf], Leaf, Node [Leaf]] !t [1]

```

```

value Node [Node [Leaf, Leaf, Leaf], Leaf, Node [Leaf]] !t [0,2]

```

**lemma** *subtrees-Leaf*:  $(t = \text{Leaf}) = (\text{subtrees } t = [])$   
**by** (*metis tree.collapse tree.sel*)

**fun** *is-subtree-index* :: *tree*  $\Rightarrow$  *nat list*  $\Rightarrow$  *bool* **where**  
*is-subtree-index*  $t [] = \text{True}$  |  
*is-subtree-index*  $t (i\#xs) = (\text{is-subtree-index } t \text{ xs} \wedge i < \text{length } (\text{subtrees } (t !t \text{ xs})))$

**lemma** *subtree-append*:  $ts ! i !t \text{ xs} = \text{Node } ts !t \text{ xs} @ [i]$   
**by** (*induction xs, auto*)

**lemma** *is-subtree-index-append* [*iff*]:  $\text{is-subtree-index } (\text{Node } ts) (\text{xs} @ [i]) =$   
 $(i < \text{length } ts \wedge \text{is-subtree-index } (ts ! i) \text{ xs})$

**proof**

**show**  $\text{is-subtree-index } (\text{Node } ts) (\text{xs} @ [i]) \Longrightarrow i < \text{length } ts \wedge \text{is-subtree-index } (ts ! i) \text{ xs}$

**by** (*induction xs, auto simp: subtree-append*)

**next**

**show**  $i < \text{length } ts \wedge \text{is-subtree-index } (ts ! i) \text{ xs} \Longrightarrow \text{is-subtree-index } (\text{Node } ts) (\text{xs} @ [i])$

**by** (*induction xs, auto simp: subtree-append*)

**qed**

**lemma** *is-subtree-index-append'* [*iff*]:  $\text{is-subtree-index } t (\text{xs} @ [i]) =$   
 $(\text{is-subtree-index } t [i] \wedge \text{is-subtree-index } (t !t [i]) \text{ xs})$   
**by** (*metis is-subtree-index-append is-subtree-index.simps subtree.simps tree.collapse*)

**lemma** *max-set-upt* [*simp*]:  $\text{Max } \{0..<\text{Suc } n\} = n$   
**by** (*simp add: Max-eq-iff*)

**lemma** *length-subtrees-eq-Max*: **assumes**  $\text{is-subtree-index } t \text{ xs}$   $\text{subtrees } (t !t \text{ xs}) \neq []$

**shows**  $\text{length } (\text{subtrees } (t !t \text{ xs})) = \text{Suc } (\text{Max } \{i. \text{is-subtree-index } t (i \# \text{xs})\})$

**proof** –

**have**  $\bigwedge i. \text{is-subtree-index } t (i \# \text{xs}) = (i < \text{length } (\text{subtrees } (t !t \text{ xs})))$  **using** *assms(1)* **by** *simp*

**hence**  $\{i. \text{is-subtree-index } t (i \# \text{xs})\} = \{0..<\text{length } (\text{subtrees } (t !t \text{ xs}))\}$  **by** *fastforce*

**moreover have**  $\text{length } (\text{subtrees } (t !t \text{ xs})) > 0$  **using** *assms(2)* **by** *simp*

**ultimately show**  $\text{length } (\text{subtrees } (t !t \text{ xs})) = \text{Suc } (\text{Max } \{i. \text{is-subtree-index } t (i \# \text{xs})\})$

**by** (*metis max-set-upt gr0-implies-Suc*)

**qed**

**lemma** *tree-eq-iff-subtree-eq*:  $(t = u) = (\text{length } (\text{subtrees } t) = \text{length } (\text{subtrees } u))$   
 $\wedge$

$(\forall i < \text{length } (\text{subtrees } t). t !t [i] = u !t [i])$

**by** (*cases t, cases u, auto simp add: list-eq-iff-nth-eq*)

We define the height of a rooted tree. A tree with only one node has height 0. The trees of height at most n encode the n-cells in 'pd'.

```

fun height :: tree ⇒ nat where
  height Leaf = 0 |
  height (Node ts) = Suc (fold (max ∘ height) ts 0)

value height Leaf
value height (Node [Leaf, Leaf])
value height (Node [Node [Leaf, Leaf], Leaf])
value height (Node [Node [Leaf, Node [Leaf]]])

lemma height-Node [simp]: ts ≠ [] ⇒ height (Node ts) = Suc (fold (max ∘ height)
  ts 0)
  by (metis height.simps(2) neq-Nil-conv)

lemma fold-eq-Max [simp]: ts ≠ [] ⇒ fold (max ∘ height) ts 0 = Max (set (map
  height ts))
  using Max.set-eq-fold fold-map list.exhaust
  by (metis (no-types, lifting) fold-simps(2) map-is-Nil-conv max-nat.right-neutral)

lemma height-Node-Max: ts ≠ [] ⇒ height (Node ts) = Suc (Max (set (map
  height ts)))
  by simp

lemma height-Node-pos : ts ≠ [] ⇒ 0 < height (Node ts)
proof (induction Node ts rule: height.induct)
  case 1
    then show ?case by blast
  next
    case (2 t ts')
    then show ?case by fastforce
qed

lemma height-exists:
  assumes height (Node ts) = Suc n
  shows ∃ t. t ∈ set ts ∧ height t = n
proof (cases ts = [])
  case True
    then show ?thesis using assms by simp
  next
    case False
    hence n = Max (set (map height ts)) using assms height-Node-Max by force
    hence n ∈ set (map height ts) using Max-in ⟨ts ≠ []⟩ by auto
    then show ?thesis by auto
qed

lemma height-lt: assumes t ∈ set ts shows height t < height (Node ts)
proof –
  from assms have nemp: ts ≠ [] by fastforce
  have height t ≤ Max (set (map height ts)) using assms by fastforce
  also have ... = fold (max ∘ height) ts 0 using nemp fold-eq-Max by simp

```

**finally show** *?thesis* **using** *nemp* **by** *simp*  
**qed**

**lemma** *height-le-imp-le-Suc*:

**assumes**  $\forall t \in \text{set } ts. \text{height } t \leq n$

**shows**  $\text{height } (\text{Node } ts) \leq \text{Suc } n$

**proof** (*cases*  $ts = []$ )

**case** *True*

**then show** *?thesis* **by** *simp*

**next**

**case** *False*

**hence**  $\text{height } (\text{Node } ts) = \text{Suc } (\text{Max } (\text{set } (\text{map } \text{height } ts)))$  **using** *height-Node-Max*  
**by** *blast*

**also have**  $\dots \leq \text{Suc } (\text{Max } (\text{height } \text{' } \text{set } ts))$  **using** *set-map* **by** *fastforce*

**finally show** *?thesis* **using**  $\langle ts \neq [] \rangle$  *assms* **by** *simp*

**qed**

**lemma** *height-zero [simp]*:  $\text{height } t = 0 \implies t = \text{Leaf}$

**by** (*metis* *height.cases* *height-Node-pos* *less-nat-zero-code*)

**lemma** *is-subtree-index-length-le*:  $\text{is-subtree-index } t \text{ } xs \implies \text{length } xs \leq \text{height } t$

**proof** (*induction*  $xs$  *arbitrary*:  $t$  *rule*: *rev-induct*)

**case** *Nil*

**then show** *?case* **by** *force*

**next**

**case** (*snoc*  $i \text{ } xs$ )

**hence**  $hi: i < \text{length } (\text{subtrees } t)$  **by** (*metis* *is-subtree-index-append* *tree.exhaust-sel*)

**hence**  $\text{length } xs \leq \text{height } (\text{subtrees } t \ ! \ i)$

**by** (*metis* *snoc* *is-subtree-index-append* *tree.exhaust-sel*)

**moreover have**  $\text{subtrees } t \ ! \ i \in \text{set } (\text{subtrees } t)$  **using**  $hi$  **by** *simp*

**ultimately show** *?case* **using** *height-lt* **by** *fastforce*

**qed**

**lemma** *height-subtree*:  $\text{is-subtree-index } t \text{ } xs \implies \text{height } (t \ ! \ xs) \leq \text{height } t - \text{length } xs$

**proof** (*induction*  $xs$  *arbitrary*:  $t$  *rule*: *rev-induct*)

**case** *Nil*

**then show** *?case* **by** *simp*

**next**

**case** (*snoc*  $i \text{ } xs$ )

**hence**  $\text{is-subtree-index } (t \ ! \ [i]) \text{ } xs$  **using** *is-subtree-index-append'* **by** *fastforce*

**hence**  $\text{height } (t \ ! \ [i] \ ! \ xs) \leq \text{height } (t \ ! \ [i]) - \text{length } xs$  **using** *snoc.IH* **by** *blast*

**moreover have**  $\text{height } (t \ ! \ [i]) < \text{height } t$

**by** (*metis* *height-lt* *is-subtree-index.simps*(2) *is-subtree-index-append'* *nth-mem* *snoc.premis*)

*subtree.simps* *tree.collapse*)

**moreover have**  $t \ ! \ [i] \ ! \ xs = t \ ! \ xs \ @ \ [i]$  **using** *subtree-append* **by** *simp*

**ultimately show** *?case* **by** *auto*

**qed**

**lemma** *height-induct*:  $(\bigwedge t. \forall u. \text{height } u < \text{height } t \longrightarrow P u \implies P t) \implies P t$   
**by** (*metis Nat.measure-induct*)

**lemma** *subtree-index-induct* [*case-names Index Step*]:

**assumes**

*is-subtree-index t xs*

$\bigwedge xs. \llbracket \text{is-subtree-index } t \text{ } xs; \forall i < \text{length } (\text{subtrees } (t \ !t \ xs)). P (i \# xs) \rrbracket \implies P xs$

**shows** *P xs*

**proof** –

**have** *hl*:  $\text{length } xs \leq \text{height } t$  **by** (*simp add: assms(1) is-subtree-index-length-le*)

**then show** *P xs* **using** *assms*

**proof** (*induction height t – length xs arbitrary: xs*)

**case** *0*

**hence**  $\text{height } (t \ !t \ xs) = 0$  **using** *height-subtree* **by** *fastforce*

**hence**  $\forall i < \text{length } (\text{subtrees } (t \ !t \ xs)). P (i \# xs)$

**by** (*metis height-zero length-0-conv less-nat-zero-code tree.sel*)

**then show** *?case* **using** *0.premis* **by** *blast*

**next**

**case** (*Suc n*)

**have**  $\forall i < \text{length } (\text{subtrees } (t \ !t \ xs)). P (i \# xs)$

**proof** (*safe*)

**fix** *i* **assume**  $i < \text{length } (\text{subtrees } (t \ !t \ xs))$

**hence** *is-subtree-index t (i # xs)* **using** *Suc(4)* **by** *simp*

**moreover hence**  $\text{length } (i \# xs) \leq \text{height } t$  **using** *is-subtree-index-length-le*

**by** *blast*

**moreover have**  $n = \text{height } t - \text{length } (i \# xs)$  **using** *Suc(2)* **by** *simp*

**ultimately show** *P (i # xs)* **using** *Suc(1) Suc(5)* **by** *blast*

**qed**

**then show** *?case* **using** *Suc.premis* **by** *blast*

**qed**

**qed**

The function *trim* keeps the first *n* layers of a tree and removes the remaining ones.

**fun** *trim* :: *nat*  $\Rightarrow$  *tree*  $\Rightarrow$  *tree* **where**

*trim 0 t = Leaf |*

*trim (Suc n) (Node ts) = Node (map (trim n) ts)*

**lemma** *trim-Leaf* [*simp*]: *trim n Leaf = Leaf*

**by** (*metis list.simps(8) trim.elims trim.simps(2)*)

**lemma** *height-trim-le*:  $\text{height } (\text{trim } n \ t) \leq n$

**proof** (*induction n t rule: trim.induct*)

**case** (*1 t*)

**then show** *?case* **by** *auto*

**next**

**case** (*2 n ts*)

**hence**  $\forall t' \in \text{set } (\text{map } (\text{trim } n) \ ts). \text{height } t' \leq n$  **by** *auto*

**then show** *?case* **using** *height-le-imp-le-Suc trim.simps(2)* **by** *presburger*  
**qed**

**lemma** *trim-const*:  $\text{height } t \leq n \implies \text{trim } n \ t = t$   
**proof** (*induction n t rule: trim.induct*)  
  **case** (1 *t*)  
  **then show** *?case* **using** *height-zero trim-Leaf* **by** *blast*  
**next**  
  **case** (2 *n ts*)  
  **hence**  $\bigwedge t. t \in \text{set } ts \implies \text{trim } n \ t = t$  **using** *height-lt* **by** *fastforce*  
  **hence**  $\text{map } (\text{trim } n) \ ts = ts$  **using** *map-idI* **by** *blast*  
  **then show** *?case* **by** *fastforce*  
**qed**

**lemma** *height-trim-le'*:  $n \leq \text{height } t \implies \text{height } (\text{trim } n \ t) = n$   
**proof** (*induction n t rule: trim.induct*)  
  **case** (1 *t*)  
  **then show** *?case* **by** *fastforce*  
**next**  
  **case** (2 *n ts*)  
  **hence**  $\exists m. \text{height } (\text{Node } ts) = \text{Suc } m$  **by** *presburger*  
  **then obtain** *m* **where** *hm*:  $\text{height } (\text{Node } ts) = \text{Suc } m$  **by** *presburger*  
  **then obtain** *t* **where** *ht*:  $t \in \text{set } ts \wedge \text{height } t = m$  **using** *height-exists* **by** *meson*  
  **have**  $n \leq m$  **using** 2 *hm* **by** *fastforce*  
  **hence** *hn*:  $\text{height } (\text{trim } n \ t) = n$  **using** 2 *ht* **by** *blast*  
  **have**  $\text{trim } n \ t \in \text{set } (\text{subtrees } (\text{trim } (\text{Suc } n) \ (\text{Node } ts)))$  **using** *ht* **by** *simp*  
  **then show** *?case* **using** *hn height-lt* **by** (*metis height-trim-le leD le-SucE tree.collapse*)  
**qed**

**lemma** *height-trim*:  $\text{height } (\text{trim } n \ t) = (\text{if } n \leq \text{height } t \text{ then } n \text{ else } \text{height } t)$   
  **using** *height-trim-le' trim-const* **by** *auto*

**value** *trim 1 Leaf*  
**value** *trim 1 (Node [Leaf, Leaf])*  
**value** *trim 2 (Node [Node [Leaf, Leaf], Leaf])*  
**value** *trim 1 (Node [Node [Leaf, Node [Leaf]], Node [Leaf]])*

**lemma** *trim-trim'* [*simp*]:  $\text{trim } n \circ \text{trim } n = \text{trim } n$   
**proof** (*induction n*)  
  **case** 0  
  **then show** *?case* **by** *simp*  
**next**  
  **case** (*Suc n*)  
  **then show** *?case* **apply** (*simp add: fun-eq-iff*) **proof**  
  **fix** *t*  
  **show**  $\text{trim } (\text{Suc } n) \ (\text{trim } (\text{Suc } n) \ t) = \text{trim } (\text{Suc } n) \ t$   
  **using** *Suc* **by** (*metis list.map-comp tree.exhaust trim.simps(2)*)  
**qed**  
**qed**

```

lemma trim-trim-Suc [simp]: trim n ◦ trim (Suc n) = trim n
proof (induction n)
  case 0
  then show ?case by simp
next
  case (Suc n)
  then show ?case apply (simp add: fun-eq-iff) proof
    fix t
    show trim (Suc n) (trim (Suc (Suc n)) t) = trim (Suc n) t
      using Suc by (metis list.map-comp tree.exhaust trim.simps(2))
  qed
qed

```

```

lemma trim-trim [simp]: n ≤ m ⇒ trim n ◦ trim m = trim n
proof (induction m arbitrary: n)
  case 0
  then show ?case by force
next
  case (Suc m)
  then show ?case proof (cases n = Suc m)
    case True
    then show ?thesis by auto
  next
    case False
    hence n ≤ m using Suc.premis by auto
    hence ih: trim n = trim n ◦ trim m using Suc by presburger
    hence trim n ◦ trim (Suc m) = (trim n ◦ trim m) ◦ trim (Suc m) by simp
    also have ... = trim n ◦ trim m by (metis fun.map-comp trim-trim-Suc)
    finally show ?thesis using ih by auto
  qed
qed

```

```

lemma trim-eq-imp-trim-eq [simp]: [[n ≤ m; trim m t = trim m u]] ⇒ trim n t
= trim n u
  by (metis trim-trim comp-apply)

```

```

lemma trim-1-eq: assumes trim 1 (Node ts) = trim 1 (Node us) shows length ts
= length us
proof –
  have ∧vs. trim 1 (Node vs) = Node (map (λx. Leaf) vs) by force
  then show ?thesis using assms map-eq-imp-length-eq by auto
qed

```

```

lemma length-subtrees-trim-Suc: length (subtrees (trim (Suc n) t)) = length (subtrees
t)
  by (induction t, simp)

```

```

lemma trim-eq-Leaf: trim n t = Leaf ⇒ n = 0 ∨ t = Leaf

```

by (induction n t rule: trim.induct, simp-all)

**lemma** map-eq-imp-pairs-eq:  $\text{map } f \text{ } xs = \text{map } g \text{ } ys \implies (\bigwedge x y. (x, y) \in \text{set } (\text{zip } xs \text{ } ys) \implies f x = g y)$   
by (metis fst-eqD in-set-zip nth-map snd-eqD)

**lemma** trim-eq-subtree-eq:

assumes  $\text{trim } (\text{Suc } n) (\text{Node } ts) = \text{trim } (\text{Suc } n) (\text{Node } us)$   
shows  $\bigwedge t u. (t, u) \in \text{set } (\text{zip } ts \text{ } us) \implies \text{trim } n \text{ } t = \text{trim } n \text{ } u$

**proof** –

fix t u assume  $(t, u) \in \text{set } (\text{zip } ts \text{ } us)$

moreover from *assms* have  $\text{map } (\text{trim } n) \text{ } ts = \text{map } (\text{trim } n) \text{ } us$  by *fastforce*  
ultimately show  $\text{trim } n \text{ } t = \text{trim } n \text{ } u$  using *map-eq-imp-pairs-eq* by *fast*

qed

**lemma** pairs-eq-imp-map-eq:

assumes  $\text{length } xs = \text{length } ys \ \forall (x, y) \in \text{set } (\text{zip } xs \text{ } ys). f x = g y$   
shows  $\text{map } f \text{ } xs = \text{map } g \text{ } ys$

**proof** –

have  $\bigwedge x y. (x, y) \in \text{set } (\text{zip } (\text{map } f \text{ } xs) (\text{map } g \text{ } ys)) \implies x = y$  **proof** –

fix x y assume  $h: (x, y) \in \text{set } (\text{zip } (\text{map } f \text{ } xs) (\text{map } g \text{ } ys))$

hence  $\exists n. (\text{map } f \text{ } xs)!n = x \wedge (\text{map } g \text{ } ys)!n = y \wedge n < \text{length } xs \wedge n < \text{length } ys$

ys

by (metis in-set-zip fst-conv length-map snd-conv)

then obtain n where  $hn: (\text{map } f \text{ } xs)!n = x \wedge (\text{map } g \text{ } ys)!n = y \wedge n < \text{length } xs \wedge n < \text{length } ys$

by *blast*

hence  $(xs!n, ys!n) \in \text{set } (\text{zip } xs \text{ } ys)$  using *in-set-zip* by *fastforce*

with  $hn$  *assms*(2) show  $x = y$  by *auto*

qed

hence  $\forall (x, y) \in \text{set } (\text{zip } (\text{map } f \text{ } xs) (\text{map } g \text{ } ys)). x = y$  by *force*

with *assms*(1) *list-eq-iff-zip-eq* show  $\text{map } f \text{ } xs = \text{map } g \text{ } ys$  by *fastforce*

qed

**lemma** map-eq-iff-pairs-eq:  $(\text{map } f \text{ } xs = \text{map } g \text{ } ys) =$

$(\text{length } xs = \text{length } ys \wedge (\forall (x, y) \in \text{set } (\text{zip } xs \text{ } ys). f x = g y))$

**proof** –

have  $\text{map } f \text{ } xs = \text{map } g \text{ } ys \implies \forall (x, y) \in \text{set } (\text{zip } xs \text{ } ys). f x = g y$  using *map-eq-imp-pairs-eq*

by *fast*

thus *thesis* by (metis *pairs-eq-imp-map-eq* *length-map*)

qed

**lemma** subtree-eq-trim-eq:

assumes  $\text{length } ts = \text{length } us \ \forall (t, u) \in \text{set } (\text{zip } ts \text{ } us). \text{trim } n \text{ } t = \text{trim } n \text{ } u$

shows  $\text{trim } (\text{Suc } n) (\text{Node } ts) = \text{trim } (\text{Suc } n) (\text{Node } us)$

by (auto simp add: *assms* *map-eq-iff-pairs-eq*)

**lemma** subtree-trim-1:  $\text{is-subtree-index } t \text{ } [i] \implies \text{trim } (\text{Suc } n) \text{ } t \text{ } !t \text{ } [i] = \text{trim } n \text{ } (t$

!t [i])  
**by** (smt (verit) Suc-inject is-subtree-index.simps(2) list.distinct(1) nat.distinct(1)  
nth-map  
subtree.elims subtree.simps(2) tree.sel trim.elims)

**lemma** *is-subtree-index-trim*:

*is-subtree-index (trim n t) xs = (is-subtree-index t xs  $\wedge$  length xs  $\leq$  n)*

**proof** (induction n t arbitrary: xs rule: trim.induct)

case (1 t)

then show ?case **using** *is-subtree-index-length-le* **by** fastforce

next

case (2 n ts)

then show ?case **proof** (induction xs rule: rev-induct)

case Nil

then show ?case **by** auto

next

case (snoc x xs)

then show ?case **by** fastforce

qed

qed

**lemma** *subtree-trim*:  $\llbracket$ is-subtree-index t xs; length xs  $\leq$  n $\rrbracket \implies$

*trim n t !t xs = trim (n - length xs) (t !t xs)*

**proof** (induction n t arbitrary: xs rule: trim.induct)

case (1 t)

then show ?case **by** simp

next

case (2 n ts)

then show ?case **proof** (cases length xs = Suc n)

case True

hence *is-subtree-index (trim (Suc n) (Node ts)) xs* **using** *is-subtree-index-trim*

2 **by** blast

hence *height (trim (Suc n) (Node ts) !t xs)  $\leq$  0*

**by** (metis *height-subtree height-trim-le True diff-is-0-eq'*)

then show ?thesis **using** True *height-zero* **by** fastforce

next

case False

then show ?thesis **proof** (cases xs rule: rev-cases)

case Nil

then show ?thesis **by** simp

next

case (snoc ys i)

**have** *hi*: *ts ! i  $\in$  set ts is-subtree-index (ts ! i) ys* **using** *snoc 2(2)* **by** *simp-all*

**have** *hl*: *length ys  $\leq$  n* **using** *snoc 2(3)* **by** *simp*

**have** *Node (map (trim n) ts) !t ys @ [i] = trim n (ts ! i) !t ys*

**by** (metis *2.prem1 is-subtree-index-append nth-map snoc subtree-append*)

**also have**  $\dots = trim (n - length ys) (ts ! i !t ys)$  **using** *2(1)* *hi hl* **by** *blast*

**finally show** *trim (Suc n) (Node ts) !t xs = trim (Suc n - length xs) (Node ts !t xs)*

by (simp add: snoc subtree-append)  
 qed  
 qed  
 qed

**lemma** *length-subtrees-trim*:  $\llbracket \text{is-subtree-index } t \text{ } xs; \text{length } xs < n \rrbracket \implies$   
 $\text{length } (\text{subtrees } (\text{trim } n \ t \ !t \ xs)) = \text{length } (\text{subtrees } (t \ !t \ xs))$   
 by (metis subtree-trim length-subtrees-trim-Suc Suc-diff-Suc less-imp-le-nat)

**lemma** *subtree-trim-Leaf*: **assumes** *is-subtree-index* (trim n t) xs t !t xs = Leaf  
**shows** trim n t !t xs = Leaf  
**proof** (cases length xs < n)  
 case True  
 then show ?thesis  
 using length-subtrees-trim assms is-subtree-index-trim subtrees-Leaf by fastforce  
 next  
 case False  
 hence length xs = n using assms(1) by (simp add: is-subtree-index-trim)  
 then show ?thesis using assms(1) is-subtree-index-trim subtree-trim by auto  
 qed

## 4.2 The strict $\omega$ -category of pasting diagrams

The function  $\delta$  acts as both the source and target map in the globular set of pasting diagrams. It is denoted  $\partial$  in Leinster [1, p. 264].

**abbreviation**  $\delta$  where  
 $\delta \equiv \text{trim}$

**value**  $\delta \ 1$  (Node [Node [Leaf, Leaf, Leaf], Leaf, Node [Leaf]])  
**value**  $\delta \ 2$  (Node [Node [Node [Leaf, Leaf], Node [Leaf, Leaf]])

**abbreviation**  $PD :: \text{nat} \Rightarrow \text{tree set}$  where  
 $PD \ n \equiv \{t. \text{height } t \leq n\}$

**interpretation** *pd*: globular-set  $PD \ \delta \ \delta$   
 by (unfold-locales, auto simp add: height-trim-le)

The generalised source and target maps have simple interpretations in terms of *trim*.

**lemma** *s'-eq-trim*: **assumes**  $n \leq m$  height  $t \leq m$  **shows**  $\text{pd.s}' \ m \ n \ t = \text{trim } n \ t$   
 using *assms*  
**proof** (induction m arbitrary: t)  
 case 0  
 moreover hence  $n = 0$  by force  
 ultimately show ?case using *pd.s'-n-n trim-const* by simp  
 next  
 case (Suc m)  
 then show ?case **proof** (cases  $n = \text{Suc } m$ )  
 case True

```

    then show ?thesis using pd.s'-n-n Suc(3) trim-const by simp
  next
    case False
    with Suc(2) have  $n \leq m$  by simp
    hence  $pd.s' (Suc\ m)\ n\ t = pd.s'\ m\ n\ (\delta\ m\ t)$  using Suc(3) by force
    also have  $\dots = \delta\ n\ (\delta\ m\ t)$  using Suc.IH height-trim-le  $\langle n \leq m \rangle$  by blast
    finally show ?thesis by (metis trim-trim  $\langle n \leq m \rangle$  comp-apply)
  qed
qed

lemma s'-eq-t':  $pd.s' = pd.t'$ 
proof (clarsimp simp add: fun-eq-iff)
  fix  $m\ n\ t$ 
  show  $pd.s'\ m\ n\ t = pd.t'\ m\ n\ t$  proof (induction m arbitrary: n t)
    case 0
    then show ?case
      using pd.s'-n-n pd.t'-n-n pd.s'.simps(2) pd.t'.simps(2) by (cases n, presburger+)
  next
    case (Suc m)
    then show ?case by (cases Suc m rule: linorder-cases, simp-all)
  qed
qed

```

**lemma**  $t'$ -eq-trim: **assumes**  $n \leq m$  **height**  $t \leq m$  **shows**  $pd.t'\ m\ n\ t = trim\ n\ t$   
**by** (metis (mono-tags, lifting) assms s'-eq-trim s'-eq-t')

Next we define identities and composition [1, p. 266]. The identity of a tree with height at most  $n$  is the same tree seen as a tree of height at most  $n + 1$ .

```

fun tree-comp ::  $nat \Rightarrow tree \Rightarrow tree \Rightarrow tree$  where
tree-comp 0 (Node ts) (Node us) = Node (ts @ us) |
tree-comp (Suc n) (Node ts) (Node us) = Node (map2 (tree-comp n) ts us)

```

```

value tree-comp 1
(Node [Node [Leaf, Leaf], Leaf, Node [Leaf]])
(Node [Leaf, Leaf, Node [Leaf, Leaf]])

```

```

value tree-comp 0
(Node [Node [Node [Leaf, Leaf]])
(Node [Node [Leaf, Leaf]])

```

```

value tree-comp 0
(tree-comp 0
(tree-comp 1

```

```

(Node [Leaf, Leaf])
(Node [Node [Leaf], Node [Leaf, Leaf, Leaf]])
(Node [Leaf, Node [Leaf, Leaf]])
(Node [Leaf, Leaf, Leaf])

```

**lemma** *tree-comp-0-Leaf1* [simp]: *tree-comp 0 Leaf t = t*  
**by** (*metis eq-Nil-appendI tree.exhaust tree-comp.simps(1)*)

**lemma** *tree-comp-0-Leaf2* [simp]: *tree-comp 0 t Leaf = t*  
**by** (*metis append-Nil2 tree.exhaust tree-comp.simps(1)*)

**lemma** *tree-comp-Suc-Leaf1* [simp]: *tree-comp (Suc n) Leaf t = Leaf*  
**by** (*cases t, simp*)

**lemma** *tree-comp-Suc-Leaf2* [simp]: *tree-comp (Suc n) t Leaf = Leaf*  
**by** (*cases t, simp*)

**lemma** *height-tree-comp-0* [simp]: *height (tree-comp 0 t u) = max (height t) (height u)*

**proof** (*cases t = Leaf ∨ u = Leaf*)

**case** *True*

**then show** *?thesis by auto*

**next**

**case** *False*

**hence** *nempt: subtrees t ≠ [] ∧ subtrees u ≠ [] by (metis tree.exhaust-sel)*

**have** *height (tree-comp 0 t u) = height (Node (subtrees t @ subtrees u))*

**by** (*metis tree.collapse tree-comp.simps(1)*)

**also have** *... = Suc (Max (set (map height (subtrees t @ subtrees u))))*

**using** *nempt height-Node-Max by blast*

**also have** *... = Suc (Max (set (map height (subtrees t) ∪ set (map height (subtrees u)))))*

**by** *simp*

**also have** *... = Suc (max (Max (set (map height (subtrees t))))*

*(Max (set (map height (subtrees u))))*)

**using** *nempt Max-Un by (metis List.finite-set map-is-Nil-conv set-empty2)*

**also have** *... = max (Suc (Max (set (map height (subtrees t))))*

*(Suc (Max (set (map height (subtrees u)))))*)

**by** *linarith*

**finally show** *height (tree-comp 0 t u) = max (height t) (height u)*

**using** *nempt height-Node-Max by (metis tree.collapse)*

**qed**

An alternative description of being composable for trees. Defined so that *tree-comp n t u* is defined if and only if *composable-tree n t u*.

**fun** *composable-tree* :: *nat ⇒ tree ⇒ tree ⇒ bool where*

*composable-tree 0 (Node ts) (Node us) = True |*

*composable-tree (Suc n) (Node ts) (Node us) = (length ts = length us ∧*

$(\forall i < \text{length } ts. \text{composable-tree } n (ts!i) (us!i))$

**lemma** *sym-composable-tree*:  $\text{composable-tree } n t u = \text{composable-tree } n u t$   
**by** (*induction*  $n t u$  *rule*: *composable-tree.induct*, *simp*, *fastforce*)

**lemma** *is-composable-pair-imp-composable-tree*:  $\text{pd.is-composable-pair } m n t u \implies$   
 $\text{composable-tree } n t u$

**proof** (*induction*  $n t u$  *rule*: *composable-tree.induct*)

**case** ( $1 ts us$ )

**then show** *?case* **by** *fastforce*

**next**

**case** ( $2 n ts us$ )

**with** *pd.is-composable-pair-def* **have**  $h: \text{Suc } n < m \text{ height } (\text{Node } ts) \leq m \text{ height } (\text{Node } us) \leq m$

$\text{pd.t}' m (\text{Suc } n) (\text{Node } us) = \text{pd.s}' m (\text{Suc } n) (\text{Node } ts)$  **by** *blast+*

**moreover hence**  $\text{Suc } n \leq m$  **by** *linarith*

**ultimately have** *htrim*:  $\text{trim } (\text{Suc } n) (\text{Node } ts) = \text{trim } (\text{Suc } n) (\text{Node } us)$

**by** (*metis* (*mono-tags*, *lifting*) *s'-eq-trim t'-eq-trim*)

**hence**  $\text{trim } 1 (\text{Node } ts) = \text{trim } 1 (\text{Node } us)$

**by** (*metis* *One-nat-def Suc-le-mono le0 trim-eq-imp-trim-eq*)

**with** *trim-1-eq* **have**  $hl: \text{length } ts = \text{length } us$  **by** *blast*

**moreover have**  $\forall i < \text{length } ts. \text{composable-tree } n (ts!i) (us!i)$  **proof** (*safe*)

**fix**  $i$  **assume**  $hi: i < \text{length } ts$

**hence**  $\text{height } (ts!i) \leq m$  **using**  $h(2)$  *height-lt nth-mem* **by** *fastforce*

**moreover have**  $\text{height } (us!i) \leq m$  **using**  $hi$   $h(3)$  *height-lt nth-mem hl* **by**

*fastforce*

**moreover have**  $n < m$  **using**  $h(1)$  **by** *simp*

**moreover have**  $\text{trim } n (ts!i) = \text{trim } n (us!i)$  **proof** –

**have**  $\text{map } (\text{trim } n) ts = \text{map } (\text{trim } n) us$  **using** *htrim* **by** *auto*

**thus**  $\text{trim } n (ts!i) = \text{trim } n (us!i)$  **using** *nth-map hi hl* **by** *metis*

**qed**

**ultimately have**  $\text{pd.t}' m n (us!i) = \text{pd.s}' m n (ts!i)$

**using** *s'-eq-trim t'-eq-trim order-less-imp-le[of n m]* **by** *presburger*

**hence** *pd.is-composable-pair*  $m n (ts!i) (us!i)$

**using** *pd.is-composable-pair-def*  $\langle n < m \rangle \langle \text{height } (ts!i) \leq m \rangle \langle \text{height } (us!i) \leq m \rangle$  **by** *blast*

**with**  $2(1)$   $hi$  **show** *composable-tree*  $n (ts!i) (us!i)$  **by** *fast*

**qed**

**ultimately show** *?case* **by** *fastforce*

**qed**

**lemma** *composable-tree-imp-trim-eq*:  $\text{composable-tree } n t u \implies \text{trim } n t = \text{trim } n u$

**proof** (*induction*  $n t u$  *rule*: *composable-tree.induct*)

**case** ( $1 ts us$ )

**then show** *?case* **by** *simp*

**next**

**case** ( $2 n ts us$ )

**then show** *?case*

**by** (*metis* (*mono-tags*, *lifting*) *nth-map trim.simps(2)* *length-map nth-equalityI*  
*composable-tree.simps(2)*)

**qed**

**lemma** *composable-tree-imp-is-composable-pair*:  
**assumes**  $n < m$  *height*  $t \leq m$  *height*  $u \leq m$  *composable-tree*  $n$   $t$   $u$   
**shows** *pd.is-composable-pair*  $m$   $n$   $t$   $u$   
**using** *assms*  
**proof** (*induction*  $m$  *arbitrary*:  $n$   $t$   $u$ )  
**case** 0  
**then show** ?*case* **by** *blast*  
**next**  
**case** (*Suc*  $m$ )  
**hence** *trim*  $n$   $u = trim$   $n$   $t$  **using** *composable-tree-imp-trim-eq* **by** *presburger*  
**hence** *pd.t'* (*Suc*  $m$ )  $n$   $u = pd.s'$  (*Suc*  $m$ )  $n$   $t$   
**using** *Suc(2-4)* *s'-eq-trim t'-eq-trim less-imp-le-nat* **by** *presburger*  
**with** *Suc(2-4)* *pd.is-composable-pair-def* **show** ?*case* **by** *blast*  
**qed**

**lemma** *is-composable-pair-iff-composable-tree*: *pd.is-composable-pair*  $m$   $n$   $t$   $u =$   
 $(n < m \wedge \text{height } t \leq m \wedge \text{height } u \leq m \wedge \text{composable-tree } n$   $t$   $u)$   
**by** (*metis* (*mono-tags*, *lifting*) *composable-tree-imp-is-composable-pair*  
*is-composable-pair-imp-composable-tree mem-Collect-eq pd.is-composable-pair-def*)

**lemma** *composable-tree-imp-composable-tree-subtrees*:  
*composable-tree* (*Suc*  $n$ ) (*Node*  $ts$ ) (*Node*  $us$ )  $\implies \forall (t, u) \in \text{set } (\text{zip } ts$   $us)$ . *com-*  
*posable-tree*  $n$   $t$   $u$   
**by** (*metis in-set-zip case-prod-beta composable-tree.simps(2)*)

**lemma** *composable-tree-nth-subtrees*:  
 $\llbracket \text{composable-tree } (\text{Suc } n) (\text{Node } ts) (\text{Node } us); i < \text{length } ts \rrbracket \implies \text{composable-tree}$   
 $n$   $(ts!i)$   $(us!i)$   
**by** *fastforce*

**lemma** *is-composable-pair-imp-is-composable-pair-subtrees*:  
**assumes** *pd.is-composable-pair* (*Suc*  $m$ ) (*Suc*  $n$ ) (*Node*  $ts$ ) (*Node*  $us$ )  
**shows**  $\forall (t, u) \in \text{set } (\text{zip } ts$   $us)$ . *pd.is-composable-pair*  $m$   $n$   $t$   $u$   
**proof**  
**have** *pd.is-composable-pair*  $m$   $n$  (*fst*  $p$ ) (*snd*  $p$ ) **if**  $hp$ :  $p \in \text{set } (\text{zip } ts$   $us)$  **for**  $p$   
**proof** –  
**have** *composable-tree* (*Suc*  $n$ ) (*Node*  $ts$ ) (*Node*  $us$ )  
**using** *is-composable-pair-iff-composable-tree assms* **by** *blast*  
**hence**  $h$ : *composable-tree*  $n$  (*fst*  $p$ ) (*snd*  $p$ )  
**using**  $hp$  *composable-tree-imp-composable-tree-subtrees* **by** *fastforce*  
**have** *fst*  $p \in \text{set } ts$  *snd*  $p \in \text{set } us$  **by** (*metis hp in-set-zipE prod.exhaust-sel*)  
**hence** *height* (*fst*  $p$ )  $\leq m$  *height* (*snd*  $p$ )  $\leq m$   
**by** (*meson hp height-lt assms less-Suc-eq-le order-less-le-trans*  
*is-composable-pair-iff-composable-tree*)  
**with**  $h$  *is-composable-pair-iff-composable-tree assms*

**show** *pd.is-composable-pair*  $m\ n\ (fst\ p)\ (snd\ p)$  **by force**  
**qed**  
**then show**  $\bigwedge x. x \in set\ (zip\ ts\ us) \implies case\ x\ of\ (t,\ u) \Rightarrow pd.is-composable-pair\ m\ n\ t\ u$   
**by force**  
**qed**

**lemma** *in-set-map2*:  $(z \in set\ (map2\ f\ xs\ ys)) = (\exists (x,\ y) \in set\ (zip\ xs\ ys). z = f\ x\ y)$   
**by auto**

**lemma** *height-tree-comp-le*:  $\llbracket height\ t \leq m; height\ u \leq m \rrbracket \implies height\ (tree-comp\ n\ t\ u) \leq m$

**proof** (*induction*  $n\ t\ u$  *arbitrary*:  $m$  *rule*: *tree-comp.induct*)  
**case**  $(1\ ts\ us)$   
**then show** *?case* **using** *height-tree-comp-0* **by presburger**  
**next**  
**case**  $(2\ n\ ts\ us)$   
**show** *?case* **proof** (*cases*  $ts \neq [] \wedge us \neq []$ )  
**case** *True*  
**hence**  $\exists m'. m = Suc\ m'$  **using** *height-zero 2.prem1* *not0-implies-Suc* **by auto**  
**then obtain**  $m'$  **where**  $m = Suc\ m'$  **by blast**  
**hence**  $\forall t \in set\ ts. height\ t \leq m' \forall u \in set\ us. height\ u \leq m'$   
**using** *True 2.prem1* **by simp+**  
**hence**  $\forall (t,\ u) \in set\ (zip\ ts\ us). height\ (tree-comp\ n\ t\ u) \leq m'$   
**by** (*metis* (*no-types, lifting*) *2.IH case-prodI2 set-zip-leftD set-zip-rightD*)  
**then show** *?thesis* **using** *True <m = Suc m'>* **by auto**  
**next**  
**case** *False*  
**then show** *?thesis* **by force**  
**qed**  
**qed**

**lemma** *nth-map2 [simp]*:  $\llbracket n < length\ xs; n < length\ ys \rrbracket \implies map2\ f\ xs\ ys\ !\ n = f\ (xs\ !\ n)\ (ys\ !\ n)$   
**by fastforce**

**lemma** *trim-tree-comp1*:  $composable-tree\ n\ t\ u \implies trim\ n\ (tree-comp\ n\ t\ u) = trim\ n\ t$

**proof** (*induction*  $n\ t\ u$  *rule*: *composable-tree.induct*)  
**case**  $(1\ ts\ us)$   
**then show** *?case* **by fastforce**  
**next**  
**case**  $(2\ n\ ts\ us)$   
**then show** *?case* **by** (*simp add: list-eq-iff-nth-eq*)  
**qed**

**lemma** *trim-tree-comp2*:  $composable-tree\ n\ t\ u \implies trim\ n\ (tree-comp\ n\ t\ u) =$

```

trim n u
  using trim-tree-comp1 composable-tree-imp-trim-eq by presburger

lemma map2-map-map': map2 f (map g xs) (map h ys) = map (λ(x, y). f (g x)
(h y)) (zip xs ys)
proof (induction xs arbitrary: ys)
  case Nil
  then show ?case by simp
next
  case (Cons a xs)
  then show ?case proof (induction ys)
    case Nil
    then show ?case by simp
  next
    case (Cons a ys)
    then show ?case by auto
  qed
qed

lemma trim-tree-comp-commute: trim m (tree-comp n t u) = tree-comp n (trim m
t) (trim m u)
proof (induction m arbitrary: n t u)
  case 0
  then show ?case by (cases n, simp-all)
next
  case (Suc m)
  then show ?case
  by (induction n t u rule: composable-tree.induct, simp-all add: list-eq-iff-nth-eq)
qed

interpretation pd-pre-cat: pre-strict-omega-category PD δ δ λ m. tree-comp λ n.
id
proof (unfold-locales)
  fix m n x' x assume pd.is-composable-pair m n x' x
  then show tree-comp n x' x ∈ PD m
  using is-composable-pair-iff-composable-tree height-tree-comp-le by auto
next
  fix n show id ∈ PD n → PD (Suc n) by simp
next
  fix m x' x assume pd.is-composable-pair (Suc m) m x' x
  then show δ m (tree-comp m x' x) = δ m x
  by (simp add: is-composable-pair-iff-composable-tree trim-tree-comp2 height-tree-comp-le)
next
  fix m x' x assume pd.is-composable-pair (Suc m) m x' x
  then show δ m (tree-comp m x' x) = δ m x'
  by (simp add: is-composable-pair-iff-composable-tree trim-tree-comp1 height-tree-comp-le)
next
  fix m n x' x assume pd.is-composable-pair (Suc m) n x' x n < m
  then show δ m (tree-comp n x' x) = tree-comp n (δ m x') (δ m x)

```

by (simp add: is-composable-pair-iff-composable-tree trim-tree-comp-commute height-tree-comp-le)

next

fix x n assume x ∈ PD n

then show δ n (id x) = x using trim-const by auto

qed

lemma tree-comp-assoc: tree-comp n (tree-comp n t u) v = tree-comp n t (tree-comp n u v)

proof (induction n t u arbitrary: v rule: composable-tree.induct)

case (1 ts us)

then show ?case by (metis append-assoc tree-comp.simps(1) tree.exhaust)

next

case (2 n ts us)

define vs where vs = subtrees v hence hv: v = Node vs by force

let ?k = min (length ts) (min (length us) (length vs))

have ∀ i < ?k. tree-comp n (tree-comp n (ts!i) (us!i)) (vs!i) =

tree-comp n (ts!i) (tree-comp n (us!i) (vs!i)) using 2.IH by auto

hence map2 (tree-comp n) (map2 (tree-comp n) ts us) vs =

map2 (tree-comp n) ts (map2 (tree-comp n) us vs) by (simp add: list-eq-iff-nth-eq)

then show ?case using hv by auto

qed

lemma i'-eq-id: n ≤ m ⇒ pd-pre-cat.i' m n = id

proof (induction m)

case 0

then show ?case using pd-pre-cat.i'.simps(1) by blast

next

case (Suc m)

then show ?case by (metis pd-pre-cat.i'-Suc id-comp le-Suc-eq pd-pre-cat.i'-n-n)

qed

lemma composable-tree-trim1: n ≤ m ⇒ composable-tree n (trim m t) t

proof (induction n t arbitrary: m rule: trim.induct)

case (1 t)

then show ?case by (metis composable-tree.simps(1) tree.exhaust)

next

case (2 n ts)

hence ∃ m'. m = Suc m' by presburger

then obtain m' where hm: m = Suc m' n ≤ m' using 2(2) by blast

moreover hence ∀ i < length ts. composable-tree n (δ m' (ts!i)) (ts!i) using

2(1) by simp

ultimately show ?case by force

qed

lemma composable-tree-trim2: n ≤ m ⇒ composable-tree n t (trim m t)

using sym-composable-tree composable-tree-trim1 by presburger

lemma tree-comp-trim1: tree-comp n (trim n t) t = t

by (induction n t rule: trim.induct, simp add: tree.exhaust, simp add: list-eq-iff-nth-eq)

**lemma** tree-comp-trim2: tree-comp n t (trim n t) = t

by (induction n t rule: trim.induct, simp add: tree.exhaust, simp add: list-eq-iff-nth-eq)

**lemma** tree-comp-exchange:

$\llbracket q < p; \text{composable-tree } p \ y' \ y; \text{composable-tree } p \ x' \ x;$   
 $\text{composable-tree } q \ y' \ x'; \text{composable-tree } q \ y \ x \rrbracket \implies$   
 $\text{tree-comp } q \ (\text{tree-comp } p \ y' \ y) \ (\text{tree-comp } p \ x' \ x) =$   
 $\text{tree-comp } p \ (\text{tree-comp } q \ y' \ x') \ (\text{tree-comp } q \ y \ x)$

**proof** (induction p y' y arbitrary: q x' x rule: composable-tree.induct)

case (1 ys' ys)

then show ?case **proof** (induction q x' x rule: composable-tree.induct)

case (1 xs' xs)

then show ?case by blast

next

case (2 q xs' xs)

then show ?case by force

qed

next

case (2 p ys' ys)

then show ?case **proof** (induction q x' x rule: composable-tree.induct)

case (1 ts us)

then show ?case by force

next

case (2 n ts us)

then show ?case by (simp add: list-eq-iff-nth-eq)

qed

qed

**interpretation** pd-cat': strict-omega-category PD  $\delta \delta \lambda m$ . tree-comp  $\lambda n$ . id

**proof** (unfold-locales)

fix m n x' x x'' assume pd.is-composable-pair m n x' x pd.is-composable-pair m n x'' x'

then show tree-comp n (tree-comp n x'' x') x = tree-comp n x'' (tree-comp n x' x)

using tree-comp-assoc is-composable-pair-iff-composable-tree by force

next

fix n m x assume n < m x  $\in$  PD m

moreover hence height x  $\leq$  m by simp

ultimately show tree-comp n (pd-pre-cat.i' m n (pd.t' m n x)) x = x

by (metis (no-types, lifting) i'-eq-id t'-eq-trim tree-comp-trim1 id-apply nat-less-le)

next

fix n m x assume n < m x  $\in$  PD m

moreover hence height x  $\leq$  m by simp

ultimately show tree-comp n x (pd-pre-cat.i' m n (pd.s' m n x)) = x

by (metis (no-types, lifting) i'-eq-id s'-eq-trim tree-comp-trim2 id-apply nat-less-le)

next

fix q p m y' y x' x assume q < p p < m

```

    pd.is-composable-pair m p y' y pd.is-composable-pair m p x' x
    pd.is-composable-pair m q y' x' pd.is-composable-pair m q y x
then show tree-comp q (tree-comp p y' y) (tree-comp p x' x) =
    tree-comp p (tree-comp q y' x') (tree-comp q y x)
using is-composable-pair-iff-composable-tree tree-comp-exchange by meson
qed (simp)

end

```

## 5 Acknowledgements

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## References

- [1] T. Leinster. *Higher operads, higher categories*. Number 298. Cambridge University Press, 2004.