

Monoidal Categories

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Abstract

Building on the formalization of basic category theory set out in the author's previous AFP article [6], the present article formalizes some basic aspects of the theory of monoidal categories. Among the notions defined here are monoidal category, monoidal functor, and equivalence of monoidal categories. The main theorems formalized are MacLane's coherence theorem and the constructions of the free monoidal category and free strict monoidal category generated by a given category. The coherence theorem is proved syntactically, using a structurally recursive approach to reduction of terms that might have some novel aspects. We also give proofs of some results given by Etingof *et al* [2], which may prove useful in a formal setting. In particular, we show that the left and right unitors need not be taken as given data in the definition of monoidal category, nor does the definition of monoidal functor need to take as given a specific isomorphism expressing the preservation of the unit object. Our definitions of monoidal category and monoidal functor are stated so as to take advantage of the economy afforded by these facts.

Revisions made subsequent to the first version of this article added material on cartesian monoidal categories; showing that the underlying category of a cartesian monoidal category is a cartesian category, and that every cartesian category extends to a cartesian monoidal category.

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Chapter 1

Introduction

A *monoidal category* is a category C equipped with a binary “tensor product” functor $\otimes : C \times C \rightarrow C$, which is associative up to a given natural isomorphism, and an object \mathcal{I} that behaves up to isomorphism like a unit for \otimes . The associativity and unit isomorphisms are assumed to satisfy certain axioms known as *coherence conditions*. Monoidal categories were introduced by Bénabou [1] and MacLane [4]. MacLane showed that the axioms for a monoidal category imply that all diagrams in a large class are commutative. This result, known as MacLane’s Coherence Theorem, is the first important result in the theory of monoidal categories.

Monoidal categories are important partly because of their ubiquity. The category of sets and functions is monoidal; more generally any category with binary products and a terminal object becomes a monoidal category if we take the categorical product as \otimes and the terminal object as \mathcal{I} . The category of vector spaces over a field, with linear maps as morphisms, not only admits monoidal structure with respect to the categorical product, but also with respect to the usual tensor product of vector spaces. Monoidal categories serve as the starting point for enriched category theory in that they provide a setting in which ordinary categories, having “homs in the category of sets,” can be generalized to “categories having homs in a monoidal category \mathcal{V} ”. In addition, the theory of monoidal categories can be regarded as a stepping stone to the theory of bicategories, as monoidal categories are the same thing as one-object bicategories.

Building on the formalization of basic category theory set out in the author’s previous AFP article [6], the present article formalizes some basic aspects of the theory of monoidal categories. In Chapter 2, we give a definition of the notion of monoidal category and develop consequences of the axioms. We then give a proof of MacLane’s coherence theorem. The proof is syntactic: we define a language of terms built from arrows of a given category C using constructors that correspond to formal composition and tensor product as well as to the associativity and unit isomorphisms and their formal inverses, we then define a mapping that interprets terms of the language in an arbitrary monoidal category D via a valuation functor $V : C \rightarrow D$, and finally we syntactically characterize a class of equations between terms that hold in any such interpretation. Among these equations are all those that relate formally parallel “canonical” terms, where a term is

canonical if the only arrows of C that are used in its construction are identities. Thus, all formally parallel canonical terms have identical interpretations in any monoidal category, which is the content of MacLane’s coherence theorem.

In Chapter 3, we define the notion of a *monoidal functor* between monoidal categories. A monoidal functor from a monoidal category C to a monoidal category D is a functor $F : C \rightarrow D$, equipped with additional data that express that the monoidal structure is preserved by F up to natural isomorphism. A monoidal functor is *strict* if it preserves the monoidal structure “on the nose” (*i.e.* the natural isomorphism is an identity). We also define the notion of an *equivalence of monoidal categories*, which is a monoidal functor $F : C \rightarrow D$ that is part of an ordinary equivalence of categories between C and D .

In Chapter 4, we use the language of terms defined in Chapter 2 to give a syntactic construction of the free monoidal category $\mathcal{F}C$ generated by a category C . The arrows $\mathcal{F}C$ are defined to be certain equivalence classes of terms, where composition and tensor product, as well as the associativity and unit isomorphisms, are determined by the syntactic operations. After proving that the construction does in fact yield a monoidal category, we establish its freeness: every functor from C to a monoidal category D extends uniquely to a strict monoidal functor from $\mathcal{F}C$ to D . We then consider the subcategory $\mathcal{F}_S C$ of $\mathcal{F}C$ whose arrows are equivalence classes of terms that we call “diagonal.” Diagonal terms amount to lists of arrows of C , composition in $\mathcal{F}_S C$ is given by elementwise composition of compatible lists of arrows, and tensor product in $\mathcal{F}_S C$ is given by concatenation of lists. We show that the subcategory $\mathcal{F}_S C$ is monoidally equivalent to the category $\mathcal{F}C$ and in addition that $\mathcal{F}_S C$ is the free strict monoidal category generated by C .

The formalizations of the notions of monoidal category and monoidal functor that we give here are not quite the traditional ones. The traditional definition of monoidal category assumes as given not only an “associator” natural isomorphism, which expresses the associativity of the tensor product, but also left and right “unitor” isomorphisms, which correspond to unit laws. However, as pointed out in [2], it is not necessary to take the unitors as given, because they are uniquely determined by the other structure and the condition that left and right tensoring with the unit object are endo-equivalences. This leads to a definition of monoidal category that requires fewer data to be given and fewer conditions to be verified in applications. As this is likely to be especially important in a formal setting, we adopt this more economical definition and go to the trouble to obtain the unitors as defined notions. A similar situation occurs with the definition of monoidal functor. The traditional definition requires two natural isomorphisms to be given: one that expresses the preservation of tensor product and another that expresses the preservation of the unit object. Once again, as indicated in [2], it is logically unnecessary to take the latter isomorphism as given, since there is a canonical definition of it in terms of the other structure. We adopt the more economical definition of monoidal functor and prove that the traditionally assumed structure can be derived from it.

Finally, the proof of the coherence theorem given here potentially has some novel aspects. A typical syntactic proof of this theorem, such as that described in [5], involves the identification, for each term constructed as a formal tensor product of the unit object \mathcal{I} and “primitive objects” (*i.e.* the elements of a given set of generators), of a “reduction”

isomorphism obtained by composing “basic reductions” in which occurrences of \mathcal{I} are eliminated using components of the left and right unitors and “parentheses are moved to one end” using components of the associator. The construction of these reductions is performed, as in [5], using an approach that can be thought of as the application of an iterative strategy for normalizing a term. My thoughts were initially along these lines, and I did succeed in producing a formal proof of the coherence theorem in this way. However, proving the termination of the reduction strategy was complicated by the necessity of using of a “rank function” on terms, and the lemmas required for the remainder of the proof had to be proved by induction on rank, which was messy. At some point, I realized that it ought to be possible to define reductions in a structurally recursive way, which would permit the lemmas in the rest of the proof to be proved by structural induction, rather than induction on rank. It took some time to find the right definitions, but in the end this approach worked out more simply, and is what is presented here.

Revision Notes

The original version of this document dates from May, 2017. The current version of this document incorporates revisions made in mid-2020 after the release of Isabelle2020. Aside from various minor improvements, the main change was the addition of a new theory, concerning cartesian monoidal categories, which coordinates with material on cartesian categories that was simultaneously added to [6]. The new theory defines “cartesian monoidal category” as an extension of “monoidal category” obtained by adding additional functors, natural transformations, and coherence conditions. The main results proved are that the underlying category of a cartesian monoidal category is a cartesian category, and that every cartesian category extends to a cartesian monoidal category.

Chapter 2

Monoidal Category

In this theory, we define the notion “monoidal category,” and develop consequences of the definition. The main result is a proof of MacLane’s coherence theorem.

```
theory MonoidalCategory  
imports Category3.EquivalenceOfCategories  
begin
```

2.1 Monoidal Category

A typical textbook presentation defines a monoidal category to be a category C equipped with (among other things) a binary “tensor product” functor $\otimes: C \times C \rightarrow C$ and an “associativity” natural isomorphism α , whose components are isomorphisms $\alpha(a, b, c): (a \otimes b) \otimes c \rightarrow a \otimes (b \otimes c)$ for objects a, b , and c of C . This way of saying things avoids an explicit definition of the functors that are the domain and codomain of α and, in particular, what category serves as the domain of these functors. The domain category is in fact the product category $C \times C \times C$ and the domain and codomain of α are the functors $T o (T \times C): C \times C \times C \rightarrow C$ and $T o (C \times T): C \times C \times C \rightarrow C$. In a formal development, though, we can’t gloss over the fact that $C \times C \times C$ has to mean either $C \times (C \times C)$ or $(C \times C) \times C$, which are not formally identical, and that associativities are somehow involved in the definitions of the functors $T o (T \times C)$ and $T o (C \times T)$. Here we use the *binary-endofunctor* locale to codify our choices about what $C \times C \times C$, $T o (T \times C)$, and $T o (C \times T)$ actually mean. In particular, we choose $C \times C \times C$ to be $C \times (C \times C)$ and define the functors $T o (T \times C)$, and $T o (C \times T)$ accordingly.

Our primary definition for “monoidal category” follows the somewhat non-traditional development in [2]. There a monoidal category is defined to be a category C equipped with a binary *tensor product* functor $T: C \times C \rightarrow C$, an *associativity isomorphism*, which is a natural isomorphism $\alpha: T o (T \times C) \rightarrow T o (C \times T)$, a *unit object* \mathcal{I} of C , and an isomorphism $\iota: T(\mathcal{I}, \mathcal{I}) \rightarrow \mathcal{I}$, subject to two axioms: the *pentagon axiom*, which expresses the commutativity of certain pentagonal diagrams involving components of α , and the left and right *unit axioms*, which state that the endofunctors $T(\mathcal{I}, -)$ and $T(-, \mathcal{I})$

\mathcal{I}) are equivalences of categories. This definition is formalized in the *monoidal-category* locale.

In more traditional developments, the definition of monoidal category involves additional left and right *unitor* isomorphisms λ and ϱ and associated axioms involving their components. However, as is shown in [2] and formalized here, the unitors are uniquely determined by α and their values $\lambda(\mathcal{I})$ and $\varrho(\mathcal{I})$ at \mathcal{I} , which coincide. Treating λ and ϱ as defined notions results in a more economical basic definition of monoidal category that requires less data to be given, and has a similar effect on the definition of “monoidal functor.” Moreover, in the context of the formalization of categories that we use here, the unit object \mathcal{I} also need not be given separately, as it can be obtained as the codomain of the isomorphism ι .

```

locale monoidal-category =
  category C +
  CC: product-category C C +
  CCC: product-category C CC.comp +
  T: binary-endofunctor C T +
   $\alpha$ : natural-isomorphism CCC.comp C T.ToTC T.ToCT  $\alpha$  +
  L: equivalence-functor C C  $\lambda f$ . T (cod  $\iota$ , f) +
  R: equivalence-functor C C  $\lambda f$ . T (f, cod  $\iota$ )
for C :: 'a comp      (infixr <·> 55)
and T :: 'a * 'a  $\Rightarrow$  'a
and  $\alpha$  :: 'a * 'a * 'a  $\Rightarrow$  'a
and  $\iota$  :: 'a +
assumes unit-in-hom-ax:  $\langle \iota : T \text{ (cod } \iota, \text{ cod } \iota) \rightarrow \text{cod } \iota \rangle$ 
and unit-is-iso: iso  $\iota$ 
and pentagon:  $\llbracket \text{ide } a; \text{ide } b; \text{ide } c; \text{ide } d \rrbracket \Longrightarrow$ 
      T (a,  $\alpha$  (b, c, d))  $\cdot$   $\alpha$  (a, T (b, c), d)  $\cdot$  T ( $\alpha$  (a, b, c), d) =
       $\alpha$  (a, b, T (c, d))  $\cdot$   $\alpha$  (T (a, b), c, d)
begin

```

We now define helpful notation and abbreviations to improve readability. We did not define and use the notation \otimes for the tensor product in the definition of the locale because to define \otimes as a binary operator requires that it be in curried form, whereas for T to be a binary functor requires that it take a pair as its argument.

```

abbreviation unity :: 'a (<\mathcal{I}>)
where unity  $\equiv$  cod  $\iota$ 

abbreviation L :: 'a  $\Rightarrow$  'a
where L f  $\equiv$  T ( $\mathcal{I}$ , f)

abbreviation R :: 'a  $\Rightarrow$  'a
where R f  $\equiv$  T (f,  $\mathcal{I}$ )

abbreviation tensor      (infixr <\mathcal{I}\otimes> 53)
where f  $\otimes$  g  $\equiv$  T (f, g)

abbreviation assoc      (<a[-, -, -]>)

```

where $a[a, b, c] \equiv \alpha(a, b, c)$

In HOL we can just give the definitions of the left and right unitors “up front” without any preliminary work. Later we will have to show that these definitions have the right properties. The next two definitions define the values of the unitors when applied to identities; that is, their components as natural transformations.

definition *lunit* ($\langle l[-] \rangle$)

where $lunit\ a \equiv THE\ f.\ \langle f : \mathcal{I} \otimes a \rightarrow a \rangle \wedge \mathcal{I} \otimes f = (\iota \otimes a) \cdot inv\ a[\mathcal{I}, \mathcal{I}, a]$

definition *runit* ($\langle r[-] \rangle$)

where $runit\ a \equiv THE\ f.\ \langle f : a \otimes \mathcal{I} \rightarrow a \rangle \wedge f \otimes \mathcal{I} = (a \otimes \iota) \cdot a[a, \mathcal{I}, \mathcal{I}]$

We now embark upon a development of the consequences of the monoidal category axioms. One of our objectives is to be able to show that an interpretation of the *monoidal-category* locale induces an interpretation of a locale corresponding to a more traditional definition of monoidal category. Another is to obtain the facts we need to prove the coherence theorem.

lemma *unit-in-hom* [*intro*]:

shows $\langle \iota : \mathcal{I} \otimes \mathcal{I} \rightarrow \mathcal{I} \rangle$

using *unit-in-hom-ax* **by** *force*

lemma *ide-unity* [*simp*]:

shows *ide* \mathcal{I}

using *unit-in-hom* **by** *auto*

lemma *tensor-in-hom* [*simp*]:

assumes $\langle f : a \rightarrow b \rangle$ **and** $\langle g : c \rightarrow d \rangle$

shows $\langle f \otimes g : a \otimes c \rightarrow b \otimes d \rangle$

using *assms T.preserves-hom CC.arr-char* **by** *simp*

lemma *tensor-in-homI* [*intro*]:

assumes $\langle f : a \rightarrow b \rangle$ **and** $\langle g : c \rightarrow d \rangle$ **and** $x = a \otimes c$ **and** $y = b \otimes d$

shows $\langle f \otimes g : x \rightarrow y \rangle$

using *assms tensor-in-hom*

by *force*

lemma *arr-tensor* [*simp*]:

assumes *arr* f **and** *arr* g

shows *arr* $(f \otimes g)$

using *assms* **by** *simp*

lemma *dom-tensor* [*simp*]:

assumes $\langle f : a \rightarrow b \rangle$ **and** $\langle g : c \rightarrow d \rangle$

shows *dom* $(f \otimes g) = a \otimes c$

using *assms* **by** *fastforce*

lemma *cod-tensor* [*simp*]:

assumes $\langle f : a \rightarrow b \rangle$ **and** $\langle g : c \rightarrow d \rangle$

shows *cod* $(f \otimes g) = b \otimes d$

using *assms* **by** *fastforce*

lemma *tensor-preserves-ide* [*simp*]:
assumes *ide a* **and** *ide b*
shows *ide (a ⊗ b)*
using *assms T.preserves-ide CC.ide-char* **by** *simp*

lemma *tensor-preserves-iso* [*simp*]:
assumes *iso f* **and** *iso g*
shows *iso (f ⊗ g)*
using *assms* **by** *simp*

lemma *inv-tensor* [*simp*]:
assumes *iso f* **and** *iso g*
shows *inv (f ⊗ g) = inv f ⊗ inv g*
using *assms T.preserves-inv* **by** *auto*

lemma *interchange*:
assumes *seq h g* **and** *seq h' g'*
shows $(h \otimes h') \cdot (g \otimes g') = h \cdot g \otimes h' \cdot g'$
using *assms T.preserves-comp* [*of (h, h') (g, g')*] **by** *simp*

lemma *α-simp*:
assumes *arr f* **and** *arr g* **and** *arr h*
shows $\alpha (f, g, h) = (f \otimes g \otimes h) \cdot a[\text{dom } f, \text{dom } g, \text{dom } h]$
using *assms α.naturality1* [*of (f, g, h)*] **by** *simp*

lemma *assoc-in-hom* [*intro*]:
assumes *ide a* **and** *ide b* **and** *ide c*
shows $\llbracket a[a, b, c] : (a \otimes b) \otimes c \rightarrow a \otimes b \otimes c \rrbracket$
using *assms CCC.in-homE* **by** *auto*

lemma *arr-assoc* [*simp*]:
assumes *ide a* **and** *ide b* **and** *ide c*
shows *arr a[a, b, c]*
using *assms assoc-in-hom* **by** *simp*

lemma *dom-assoc* [*simp*]:
assumes *ide a* **and** *ide b* **and** *ide c*
shows *dom a[a, b, c] = (a ⊗ b) ⊗ c*
using *assms assoc-in-hom* **by** *simp*

lemma *cod-assoc* [*simp*]:
assumes *ide a* **and** *ide b* **and** *ide c*
shows *cod a[a, b, c] = a ⊗ b ⊗ c*
using *assms assoc-in-hom* **by** *simp*

lemma *assoc-naturality*:
assumes *arr f0* **and** *arr f1* **and** *arr f2*

shows $a[\text{cod } f0, \text{cod } f1, \text{cod } f2] \cdot ((f0 \otimes f1) \otimes f2) =$
 $(f0 \otimes f1 \otimes f2) \cdot a[\text{dom } f0, \text{dom } f1, \text{dom } f2]$
using *assms* $\alpha.\text{naturality}$ **by** *auto*

lemma *iso-assoc* [*simp*]:
assumes *ide a* **and** *ide b* **and** *ide c*
shows *iso* $a[a, b, c]$
using *assms* $\alpha.\text{preserves-iso}$ **by** *simp*

The next result uses the fact that the functor L is an equivalence (and hence faithful) to show the existence of a unique solution to the characteristic equation used in the definition of a component $l[a]$ of the left unitor. It follows that $l[a]$, as given by our definition using definite description, satisfies this characteristic equation and is therefore uniquely determined by \otimes , α , and ι .

lemma *lunit-char*:
assumes *ide a*
shows $\langle l[a] : \mathcal{I} \otimes a \rightarrow a \rangle$ **and** $\mathcal{I} \otimes l[a] = (\iota \otimes a) \cdot \text{inv } a[\mathcal{I}, \mathcal{I}, a]$
and $\exists! f. \langle f : \mathcal{I} \otimes a \rightarrow a \rangle \wedge \mathcal{I} \otimes f = (\iota \otimes a) \cdot \text{inv } a[\mathcal{I}, \mathcal{I}, a]$
proof –
obtain $F \eta \varepsilon$ **where** L : *equivalence-of-categories* $C \ C \ F$ $(\lambda f. \mathcal{I} \otimes f) \eta \varepsilon$
using $L.\text{induces-equivalence}$ **by** *auto*
interpret L : *equivalence-of-categories* $C \ C \ F$ $\langle \lambda f. \mathcal{I} \otimes f \rangle \eta \varepsilon$
using L **by** *auto*
let $?P = \lambda f. \langle f : \mathcal{I} \otimes a \rightarrow a \rangle \wedge \mathcal{I} \otimes f = (\iota \otimes a) \cdot \text{inv } a[\mathcal{I}, \mathcal{I}, a]$
show $\exists! f. ?P f$
proof –
have $\exists f. ?P f$
proof –
have $\langle (\iota \otimes a) \cdot \text{inv } a[\mathcal{I}, \mathcal{I}, a] : \mathcal{I} \otimes \mathcal{I} \otimes a \rightarrow \mathcal{I} \otimes a \rangle$
proof
show $\langle \iota \otimes a : (\mathcal{I} \otimes \mathcal{I}) \otimes a \rightarrow \mathcal{I} \otimes a \rangle$
using *assms* ide-in-hom **by** *blast*
show $\langle \text{inv } a[\mathcal{I}, \mathcal{I}, a] : \mathcal{I} \otimes \mathcal{I} \otimes a \rightarrow (\mathcal{I} \otimes \mathcal{I}) \otimes a \rangle$
using *assms* **by** *auto*
qed
moreover **have** *ide* $(\mathcal{I} \otimes a)$ **using** *assms* **by** *simp*
ultimately **show** *?thesis*
using *assms* $L.\text{is-full}$ **by** *blast*
qed
moreover **have** $\bigwedge f f'. ?P f \implies ?P f' \implies f = f'$
by (*metis* $L.\text{is-faithful-in-homE}$)
ultimately **show** *?thesis* **by** *blast*
qed
hence $1: ?P l[a]$
unfolding *lunit-def* **using** *theI'* [*of ?P*] **by** *auto*
show $\langle l[a] : \mathcal{I} \otimes a \rightarrow a \rangle$ **using** 1 **by** *fast*
show $\mathcal{I} \otimes l[a] = (\iota \otimes a) \cdot \text{inv } a[\mathcal{I}, \mathcal{I}, a]$ **using** 1 **by** *fast*
qed

lemma *lunit-in-hom* [*intro*]:
assumes *ide a*
shows $\llbracket a \rrbracket : \mathcal{I} \otimes a \rightarrow a$
using *assms lunit-char(1)* **by** *blast*

lemma *arr-lunit* [*simp*]:
assumes *ide a*
shows *arr* $\llbracket a \rrbracket$
using *assms lunit-in-hom* **by** *auto*

lemma *dom-lunit* [*simp*]:
assumes *ide a*
shows *dom* $\llbracket a \rrbracket = \mathcal{I} \otimes a$
using *assms lunit-in-hom* **by** *auto*

lemma *cod-lunit* [*simp*]:
assumes *ide a*
shows *cod* $\llbracket a \rrbracket = a$
using *assms lunit-in-hom* **by** *auto*

As the right-hand side of the characteristic equation for $\mathcal{I} \otimes \llbracket a \rrbracket$ is an isomorphism, and the equivalence functor L reflects isomorphisms, it follows that $\llbracket a \rrbracket$ is an isomorphism.

lemma *iso-lunit* [*simp*]:
assumes *ide a*
shows *iso* $\llbracket a \rrbracket$
using *assms lunit-char(2) unit-is-iso ide-unity isos-compose iso-assoc iso-inv-iso unit-in-hom L.reflects-iso arr-lunit arr-tensor ideD(1) ide-is-iso lunit-in-hom tensor-preserves-iso*
by *metis*

To prove that an arrow f is equal to $\llbracket a \rrbracket$ we need only show that it is parallel to $\llbracket a \rrbracket$ and that $\mathcal{I} \otimes f$ satisfies the same characteristic equation as $\mathcal{I} \otimes \llbracket a \rrbracket$ does.

lemma *lunit-eqI*:
assumes $\langle\langle f : \mathcal{I} \otimes a \rightarrow a \rangle\rangle$ **and** $\mathcal{I} \otimes f = (\iota \otimes a) \cdot \text{inv } a[\mathcal{I}, \mathcal{I}, a]$
shows $f = \llbracket a \rrbracket$
proof –
have *ide a* **using** *assms(1)* **by** *auto*
thus *?thesis*
using *assms lunit-char the1-equality* **by** *blast*
qed

The next facts establish the corresponding results for the components of the right unitor.

lemma *runit-char*:
assumes *ide a*
shows $\langle\langle r[a] : a \otimes \mathcal{I} \rightarrow a \rangle\rangle$ **and** $r[a] \otimes \mathcal{I} = (a \otimes \iota) \cdot a[a, \mathcal{I}, \mathcal{I}]$
and $\exists ! f. \langle\langle f : a \otimes \mathcal{I} \rightarrow a \rangle\rangle \wedge f \otimes \mathcal{I} = (a \otimes \iota) \cdot a[a, \mathcal{I}, \mathcal{I}]$
proof –
obtain $F \eta \varepsilon$ **where** *R: equivalence-of-categories C C F* $(\lambda f. f \otimes \mathcal{I}) \eta \varepsilon$

using *R.induces-equivalence* **by** *auto*
interpret *R: equivalence-of-categories C C F* $\langle \lambda f. f \otimes \mathcal{I} \rangle \eta \varepsilon$
using *R* **by** *auto*
let $?P = \lambda f. \langle f : a \otimes \mathcal{I} \rightarrow a \rangle \wedge f \otimes \mathcal{I} = (a \otimes \iota) \cdot a[a, \mathcal{I}, \mathcal{I}]$
show $\exists ! f. ?P f$
proof –
have $\exists f. ?P f$
proof –
have $\langle (a \otimes \iota) \cdot a[a, \mathcal{I}, \mathcal{I}] : (a \otimes \mathcal{I}) \otimes \mathcal{I} \rightarrow a \otimes \mathcal{I} \rangle$
using *assms* **by** *fastforce*
moreover **have** *ide* $(a \otimes \mathcal{I})$ **using** *assms* **by** *simp*
ultimately **show** *?thesis*
using *assms* *R.is-full* $[of\ a\ a \otimes \mathcal{I}\ (a \otimes \iota) \cdot a[a, \mathcal{I}, \mathcal{I}]]$ **by** *blast*
qed
moreover **have** $\bigwedge f f'. ?P f \implies ?P f' \implies f = f'$
by *(metis R.is-faithful in-homE)*
ultimately **show** *?thesis* **by** *blast*
qed
hence $1: ?P\ r[a]$ **unfolding** *runit-def* **using** *theI'* $[of\ ?P]$ **by** *fast*
show $\langle r[a] : a \otimes \mathcal{I} \rightarrow a \rangle$ **using** 1 **by** *fast*
show $r[a] \otimes \mathcal{I} = (a \otimes \iota) \cdot a[a, \mathcal{I}, \mathcal{I}]$ **using** 1 **by** *fast*
qed

lemma *runit-in-hom* $[intro]$:
assumes *ide a*
shows $\langle r[a] : a \otimes \mathcal{I} \rightarrow a \rangle$
using *assms* *runit-char(1)* **by** *blast*

lemma *arr-runit* $[simp]$:
assumes *ide a*
shows *arr* $r[a]$
using *assms* *runit-in-hom* **by** *blast*

lemma *dom-runit* $[simp]$:
assumes *ide a*
shows *dom* $r[a] = a \otimes \mathcal{I}$
using *assms* *runit-in-hom* **by** *blast*

lemma *cod-runit* $[simp]$:
assumes *ide a*
shows *cod* $r[a] = a$
using *assms* *runit-in-hom* **by** *blast*

lemma *runit-eqI*:
assumes $\langle f : a \otimes \mathcal{I} \rightarrow a \rangle$ **and** $f \otimes \mathcal{I} = (a \otimes \iota) \cdot a[a, \mathcal{I}, \mathcal{I}]$
shows $f = r[a]$
proof –
have *ide a* **using** *assms(1)* **by** *auto*
thus *?thesis*

using *assms* *runit-char* *the1-equality* **by** *blast*
qed

lemma *iso-runit* [*simp*]:

assumes *ide a*

shows *iso r[a]*

using *assms* *unit-is-iso* *iso-inv-iso* *isos-compose* *ide-is-iso* *R.preserves-reflects-arr*
arrI *ide-unity* *iso-assoc* *runit-char* *tensor-preserves-iso* *R.reflects-iso*
by *metis*

We can now show that the components of the left and right unitors have the naturality properties required of a natural transformation.

lemma *lunit-naturality*:

assumes *arr f*

shows $l[\text{cod } f] \cdot (\mathcal{I} \otimes f) = f \cdot l[\text{dom } f]$

proof –

interpret α' : *inverse-transformation* *CCC.comp* *C* *T.ToTC* *T.ToCT* α ..

have *par*: *par* ($l[\text{cod } f] \cdot (\mathcal{I} \otimes f)$) ($f \cdot l[\text{dom } f]$)

using *assms* **by** *simp*

moreover **have** $\mathcal{I} \otimes l[\text{cod } f] \cdot (\mathcal{I} \otimes f) = \mathcal{I} \otimes f \cdot l[\text{dom } f]$

proof –

have $\mathcal{I} \otimes l[\text{cod } f] \cdot (\mathcal{I} \otimes f) = ((\iota \otimes \text{cod } f) \cdot ((\mathcal{I} \otimes \mathcal{I}) \otimes f)) \cdot \text{inv } a[\mathcal{I}, \mathcal{I}, \text{dom } f]$

using *assms* *interchange* [*of* $\mathcal{I} \mathcal{I} \mathcal{I} \otimes f$ $l[\text{cod } f]$] *lunit-char*(2)

α' .*naturality* [*of* $(\mathcal{I}, \mathcal{I}, f)$] *comp-assoc*

by *auto*

also **have** $\dots = ((\mathcal{I} \otimes f) \cdot (\iota \otimes \text{dom } f)) \cdot \text{inv } a[\mathcal{I}, \mathcal{I}, \text{dom } f]$

using *assms* *interchange* *comp-arr-dom* *comp-cod-arr* *unit-in-hom* **by** *auto*

also **have** $\dots = (\mathcal{I} \otimes f) \cdot (\mathcal{I} \otimes l[\text{dom } f])$

using *assms* *lunit-char*(2) *comp-assoc* **by** *auto*

also **have** $\dots = \mathcal{I} \otimes f \cdot l[\text{dom } f]$

using *assms* *interchange* *L.preserves-comp* *par* **by** *metis*

finally **show** *?thesis* **by** *blast*

qed

ultimately **show** $l[\text{cod } f] \cdot (\mathcal{I} \otimes f) = f \cdot l[\text{dom } f]$

using *L.is-faithful* **by** *metis*

qed

lemma *runit-naturality*:

assumes *arr f*

shows $r[\text{cod } f] \cdot (f \otimes \mathcal{I}) = f \cdot r[\text{dom } f]$

proof –

have *par*: *par* ($r[\text{cod } f] \cdot (f \otimes \mathcal{I})$) ($f \cdot r[\text{dom } f]$)

using *assms* **by** *force*

moreover **have** $r[\text{cod } f] \cdot (f \otimes \mathcal{I}) \otimes \mathcal{I} = f \cdot r[\text{dom } f] \otimes \mathcal{I}$

proof –

have $r[\text{cod } f] \cdot (f \otimes \mathcal{I}) \otimes \mathcal{I} = (\text{cod } f \otimes \iota) \cdot a[\text{cod } f, \mathcal{I}, \mathcal{I}] \cdot ((f \otimes \mathcal{I}) \otimes \mathcal{I})$

using *assms* *interchange* [*of* $\mathcal{I} \mathcal{I} \mathcal{I} \otimes f$ $r[\text{cod } f]$] *runit-char*(2)

comp-assoc

by *auto*

```

also have ... = (cod f ⊗ ι) · (f ⊗ I ⊗ I) · a[dom f, I, I]
  using assms α.naturality [of (f, I, I)] by auto
also have ... = ((cod f ⊗ ι) · (f ⊗ I ⊗ I)) · a[dom f, I, I]
  using comp-assoc by simp
also have ... = ((f ⊗ I) · (dom f ⊗ ι)) · a[dom f, I, I]
  using assms unit-in-hom interchange comp-arr-dom comp-cod-arr by auto
also have ... = (f ⊗ I) · (r[dom f] ⊗ I)
  using assms runit-char comp-assoc by auto
also have ... = f · r[dom f] ⊗ I
  using assms interchange R.preserves-comp par by metis
finally show ?thesis by blast
qed
ultimately show r[cod f] · (f ⊗ I) = f · r[dom f]
  using R.is-faithful by metis
qed

```

The next two definitions extend the unitors to all arrows, not just identities. Unfortunately, the traditional symbol λ for the left unitor is already reserved for a higher purpose, so we have to make do with a poor substitute.

```

abbreviation l
where l f ≡ if arr f then f · l[dom f] else null

```

```

abbreviation ρ
where ρ f ≡ if arr f then f · r[dom f] else null

```

```

lemma l-ide-simp:
assumes ide a
shows l a = l[a]
  using assms lunit-char comp-cod-arr ide-in-hom by (metis in-homE)

```

```

lemma ρ-ide-simp:
assumes ide a
shows ρ a = r[a]
  using assms runit-char [of a] comp-cod-arr by auto

```

end

```

context monoidal-category
begin

```

```

sublocale l: natural-transformation C C L map l
proof –
  interpret l: transformation-by-components C C L map ⟨λa. l[a]⟩
  using lunit-in-hom lunit-naturality unit-in-hom-ax L.extensionality
  by (unfold-locales, auto)
  have l.map = l
  using l.naturality1 l.extensionality by auto
  thus natural-transformation C C L map l
  using l.natural-transformation-axioms by auto

```

qed

sublocale \mathfrak{l} : *natural-isomorphism* $C C L$ map \mathfrak{l}
 apply *unfold-locales*
 using *iso-lunit* *l-ide-simp* **by** *simp*

sublocale ϱ : *natural-transformation* $C C R$ map ϱ
proof –
 interpret ϱ : *transformation-by-components* $C C R$ map $\langle \lambda a. \mathfrak{r}[a] \rangle$
 using *runit-naturality* *unit-in-hom-ax* *R.extensionality*
 by (*unfold-locales*, *auto*)
 have $\varrho.\text{map} = \varrho$
 using $\varrho.\text{naturality1}$ $\varrho.\text{extensionality}$ **by** *auto*
 thus *natural-transformation* $C C R$ map ϱ
 using $\varrho.\text{natural-transformation-axioms}$ **by** *auto*
qed

sublocale ϱ : *natural-isomorphism* $C C R$ map ϱ
 apply *unfold-locales*
 using $\varrho.\text{ide-simp}$ **by** *simp*

sublocale \mathfrak{l}' : *inverse-transformation* $C C L$ map $\mathfrak{l} ..$
sublocale ϱ' : *inverse-transformation* $C C R$ map $\varrho ..$
sublocale α' : *inverse-transformation* *CCC.comp* $C T.\text{ToTC}$ $T.\text{ToCT}$ $\alpha ..$

abbreviation α'
where $\alpha' \equiv \alpha'.\text{map}$

abbreviation *assoc'* ($\langle \mathfrak{a}^{-1}[-, -, -] \rangle$)
where $\mathfrak{a}^{-1}[a, b, c] \equiv \text{inv } \mathfrak{a}[a, b, c]$

lemma $\alpha'.$ *ide-simp*:
assumes *ide a* **and** *ide b* **and** *ide c*
shows $\alpha'(a, b, c) = \mathfrak{a}^{-1}[a, b, c]$
 using *assms* $\alpha'.\text{inverts-components}$ *inverse-unique* **by** *force*

lemma $\alpha'.$ *simp*:
assumes *arr f* **and** *arr g* **and** *arr h*
shows $\alpha'(f, g, h) = ((f \otimes g) \otimes h) \cdot \mathfrak{a}^{-1}[\text{dom } f, \text{dom } g, \text{dom } h]$
 using *assms* *T.ToTC-simp* $\alpha'.\text{naturality1}$ $\alpha'.$ *ide-simp* **by** *force*

lemma *assoc-inv*:
assumes *ide a* **and** *ide b* **and** *ide c*
shows *inverse-arrows* $\mathfrak{a}[a, b, c]$ $\mathfrak{a}^{-1}[a, b, c]$
 using *assms* *inv-is-inverse* **by** *simp*

lemma *assoc'-in-hom* [*intro*]:
assumes *ide a* **and** *ide b* **and** *ide c*
shows $\langle \mathfrak{a}^{-1}[a, b, c] : a \otimes b \otimes c \rightarrow (a \otimes b) \otimes c \rangle$

using *assms* **by** *auto*

lemma *arr-assoc'* [*simp*]:
assumes *ide a* **and** *ide b* **and** *ide c*
shows $\text{arr } a^{-1}[a, b, c]$
using *assms* **by** *simp*

lemma *dom-assoc'* [*simp*]:
assumes *ide a* **and** *ide b* **and** *ide c*
shows $\text{dom } a^{-1}[a, b, c] = a \otimes b \otimes c$
using *assms* **by** *simp*

lemma *cod-assoc'* [*simp*]:
assumes *ide a* **and** *ide b* **and** *ide c*
shows $\text{cod } a^{-1}[a, b, c] = (a \otimes b) \otimes c$
using *assms* **by** *simp*

lemma *comp-assoc-assoc'* [*simp*]:
assumes *ide a* **and** *ide b* **and** *ide c*
shows $a[a, b, c] \cdot a^{-1}[a, b, c] = a \otimes (b \otimes c)$
and $a^{-1}[a, b, c] \cdot a[a, b, c] = (a \otimes b) \otimes c$
using *assms* *assoc-inv* *comp-arr-inv* *comp-inv-arr* **by** *auto*

lemma *assoc'-naturality*:
assumes *arr f0* **and** *arr f1* **and** *arr f2*
shows $((f0 \otimes f1) \otimes f2) \cdot a^{-1}[\text{dom } f0, \text{dom } f1, \text{dom } f2] =$
 $a^{-1}[\text{cod } f0, \text{cod } f1, \text{cod } f2] \cdot (f0 \otimes f1 \otimes f2)$
using *assms* *α'.naturality* **by** *auto*

abbreviation *l'*
where $l' \equiv l'.\text{map}$

abbreviation *lunit'* $(\langle l^{-1}[-] \rangle)$
where $l^{-1}[a] \equiv \text{inv } l[a]$

lemma *l'-ide-simp*:
assumes *ide a*
shows $l'.\text{map } a = l^{-1}[a]$
using *assms* *l'.inverts-components* *l'-ide-simp* *inverse-unique* **by** *force*

lemma *lunit-inv*:
assumes *ide a*
shows *inverse-arrows* $l[a] \ l^{-1}[a]$
using *assms* *inv-is-inverse* **by** *simp*

lemma *lunit'-in-hom* [*intro*]:
assumes *ide a*
shows $\langle l^{-1}[a] : a \rightarrow \mathcal{I} \otimes a \rangle$
using *assms* **by** *auto*

lemma *comp-lunit-lunit'* [*simp*]:
assumes *ide a*
shows $l[a] \cdot l^{-1}[a] = a$
and $l^{-1}[a] \cdot l[a] = \mathcal{I} \otimes a$
proof –
 show $l[a] \cdot l^{-1}[a] = a$
 using *assms comp-arr-inv lunit-inv* **by** *fastforce*
 show $l^{-1}[a] \cdot l[a] = \mathcal{I} \otimes a$
 using *assms comp-arr-inv lunit-inv* **by** *fastforce*
qed

lemma *lunit'-naturality*:
assumes *arr f*
shows $(\mathcal{I} \otimes f) \cdot l^{-1}[\text{dom } f] = l^{-1}[\text{cod } f] \cdot f$
 using *assms l'.naturality l'-ide-simp* **by** *simp*

abbreviation ϱ'
where $\varrho' \equiv \varrho'.\text{map}$

abbreviation *runit'* ($\langle r^{-1}[-] \rangle$)
where $r^{-1}[a] \equiv \text{inv } r[a]$

lemma *ϱ'-ide-simp*:
assumes *ide a*
shows $\varrho'.\text{map } a = r^{-1}[a]$
 using *assms ϱ'.inverts-components ϱ-ide-simp inverse-unique* **by** *auto*

lemma *runit-inv*:
assumes *ide a*
shows *inverse-arrows* $r[a] \ r^{-1}[a]$
 using *assms inv-is-inverse* **by** *simp*

lemma *runit'-in-hom* [*intro*]:
assumes *ide a*
shows $\langle r^{-1}[a] : a \rightarrow a \otimes \mathcal{I} \rangle$
 using *assms* **by** *auto*

lemma *comp-runit-runit'* [*simp*]:
assumes *ide a*
shows $r[a] \cdot r^{-1}[a] = a$
and $r^{-1}[a] \cdot r[a] = a \otimes \mathcal{I}$
proof –
 show $r[a] \cdot r^{-1}[a] = a$
 using *assms runit-inv* **by** *fastforce*
 show $r^{-1}[a] \cdot r[a] = a \otimes \mathcal{I}$
 using *assms runit-inv* **by** *fastforce*
qed

lemma *runit'-naturality*:
assumes *arr f*
shows $(f \otimes \mathcal{I}) \cdot r^{-1}[\text{dom } f] = r^{-1}[\text{cod } f] \cdot f$
using *assms* ϱ' .*naturality* ϱ' .*ide-simp* **by** *simp*

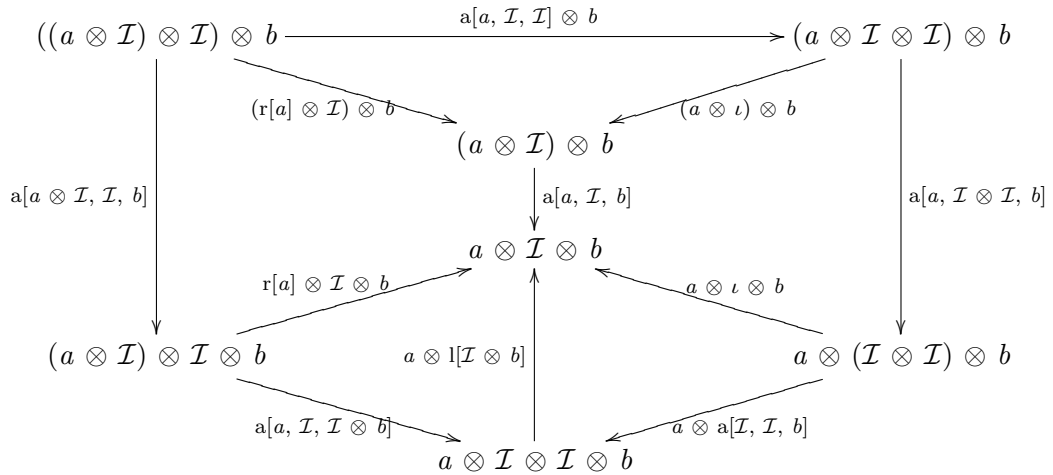
lemma *lunit-commutes-with-L*:
assumes *ide a*
shows $l[\mathcal{I} \otimes a] = \mathcal{I} \otimes l[a]$
using *assms* *lunit-naturality* *lunit-in-hom* *iso-lunit* *iso-is-section*
section-is-mono *mono-cancel* *L.preserves-ide* *arrI* *cod-lunit*
dom-lunit *seqI*
by *metis*

lemma *runit-commutes-with-R*:
assumes *ide a*
shows $r[a \otimes \mathcal{I}] = r[a] \otimes \mathcal{I}$
using *assms* *runit-naturality* *runit-in-hom* *iso-runit* *iso-is-section*
section-is-mono *mono-cancel* *R.preserves-ide* *arrI* *cod-runit*
dom-runit *seqI*
by *metis*

The components of the left and right unitors are related via a “triangle” diagram that also involves the associator. The proof follows [2], Proposition 2.2.3.

lemma *triangle*:
assumes *ide a* **and** *ide b*
shows $(a \otimes l[b]) \cdot a[a, \mathcal{I}, b] = r[a] \otimes b$
proof –

We show that the lower left triangle in the following diagram commutes.



have *: $(a \otimes l[\mathcal{I} \otimes b]) \cdot a[a, \mathcal{I}, \mathcal{I} \otimes b] = r[a] \otimes \mathcal{I} \otimes b$
proof –

have 1 : $((a \otimes l[\mathcal{I} \otimes b]) \cdot a[a, \mathcal{I}, \mathcal{I} \otimes b]) \cdot a[a \otimes \mathcal{I}, \mathcal{I}, b]$
 $= (r[a] \otimes \mathcal{I} \otimes b) \cdot a[a \otimes \mathcal{I}, \mathcal{I}, b]$

proof –

have $((a \otimes l[\mathcal{I} \otimes b]) \cdot a[a, \mathcal{I}, \mathcal{I} \otimes b]) \cdot a[a \otimes \mathcal{I}, \mathcal{I}, b] =$
 $((a \otimes l[\mathcal{I} \otimes b]) \cdot (a \otimes a[\mathcal{I}, \mathcal{I}, b])) \cdot a[a, \mathcal{I} \otimes \mathcal{I}, b] \cdot (a[a, \mathcal{I}, \mathcal{I}] \otimes b)$

using *assms pentagon comp-assoc* **by** *auto*

also have $\dots = (a \otimes ((\mathcal{I} \otimes l[b]) \cdot a[\mathcal{I}, \mathcal{I}, b])) \cdot a[a, \mathcal{I} \otimes \mathcal{I}, b] \cdot (a[a, \mathcal{I}, \mathcal{I}] \otimes b)$

using *assms interchange lunit-commutes-with-L* **by** *simp*

also have $\dots = ((a \otimes (\iota \otimes b)) \cdot a[a, \mathcal{I} \otimes \mathcal{I}, b]) \cdot (a[a, \mathcal{I}, \mathcal{I}] \otimes b)$

using *assms lunit-char unit-in-hom comp-arr-dom comp-assoc* **by** *auto*

also have $\dots = (a[a, \mathcal{I}, b] \cdot ((a \otimes \iota) \otimes b)) \cdot (a[a, \mathcal{I}, \mathcal{I}] \otimes b)$

using *assms unit-in-hom assoc-naturality [of a ι b]* **by** *fastforce*

also have $\dots = a[a, \mathcal{I}, b] \cdot ((r[a] \otimes \mathcal{I}) \otimes b)$

using *assms unit-in-hom interchange runit-char(2) comp-assoc* **by** *auto*

also have $\dots = (r[a] \otimes \mathcal{I} \otimes b) \cdot a[a \otimes \mathcal{I}, \mathcal{I}, b]$

using *assms assoc-naturality [of r[a] \mathcal{I} b]* **by** *simp*

finally show *?thesis* **by** *blast*

qed

show *?thesis*

proof –

have *epi* $a[a \otimes \mathcal{I}, \mathcal{I}, b]$

using *assms iso-assoc iso-is-retraction retraction-is-epi* **by** *simp*

thus *?thesis*

using 1 *assms*

epi-cancel [of a[a \otimes \mathcal{I} , \mathcal{I} , b] (a \otimes l[$\mathcal{I} \otimes$ b]) \cdot a[a, \mathcal{I} , $\mathcal{I} \otimes$ b]]

by *fastforce*

qed

qed

In [2] it merely states that the preceding result suffices “because any object of C is isomorphic to one of the form $\mathcal{I} \otimes b$.” However, it seems a little bit more involved than that to formally transport the equation (*) along the isomorphism $l[b]$ from $\mathcal{I} \otimes b$ to b .

have $(a \otimes l[b]) \cdot a[a, \mathcal{I}, b] = ((a \otimes l[b]) \cdot (a \otimes l[\mathcal{I} \otimes b]) \cdot (a \otimes \mathcal{I} \otimes l^{-1}[b])) \cdot$
 $(a \otimes \mathcal{I} \otimes l[b]) \cdot a[a, \mathcal{I}, \mathcal{I} \otimes b] \cdot ((a \otimes \mathcal{I}) \otimes l^{-1}[b])$

proof –

have $a[a, \mathcal{I}, b] = (a \otimes \mathcal{I} \otimes l[b]) \cdot a[a, \mathcal{I}, \mathcal{I} \otimes b] \cdot ((a \otimes \mathcal{I}) \otimes l^{-1}[b])$

proof –

have $(a \otimes \mathcal{I} \otimes l[b]) \cdot a[a, \mathcal{I}, \mathcal{I} \otimes b] \cdot ((a \otimes \mathcal{I}) \otimes l^{-1}[b])$
 $= ((a \otimes \mathcal{I} \otimes l[b]) \cdot (a \otimes \mathcal{I} \otimes l^{-1}[b])) \cdot a[a, \mathcal{I}, b]$

using *assms assoc-naturality [of a \mathcal{I} $l^{-1}[b]$]* *comp-assoc* **by** *simp*

also have $\dots = a[a, \mathcal{I}, b]$

using *assms inv-is-inverse interchange comp-cod-arr* **by** *simp*

finally show *?thesis* **by** *auto*

qed

moreover have $a \otimes l[b] = (a \otimes l[b]) \cdot (a \otimes l[\mathcal{I} \otimes b]) \cdot (a \otimes \mathcal{I} \otimes l^{-1}[b])$

using *assms lunit-commutes-with-L comp-arr-dom interchange* **by** *auto*

ultimately show *?thesis* **by** *argo*

qed

also have $\dots = (a \otimes l[b]) \cdot (a \otimes l[\mathcal{I} \otimes b]) \cdot ((a \otimes \mathcal{I} \otimes l^{-1}[b]) \cdot (a \otimes \mathcal{I} \otimes l[b])) \cdot$

$a[a, \mathcal{I}, \mathcal{I} \otimes b] \cdot ((a \otimes \mathcal{I}) \otimes l^{-1}[b])$
using *assms comp-assoc* **by** *auto*
also have $\dots = (a \otimes l[b]) \cdot ((a \otimes l[\mathcal{I} \otimes b]) \cdot a[a, \mathcal{I}, \mathcal{I} \otimes b]) \cdot ((a \otimes \mathcal{I}) \otimes l^{-1}[b])$
using *assms interchange comp-cod-arr comp-assoc* **by** *auto*
also have $\dots = r[a] \otimes b$
using *assms * interchange runit-char(1) comp-arr-dom comp-cod-arr* **by** *auto*
finally show *?thesis* **by** *blast*
qed

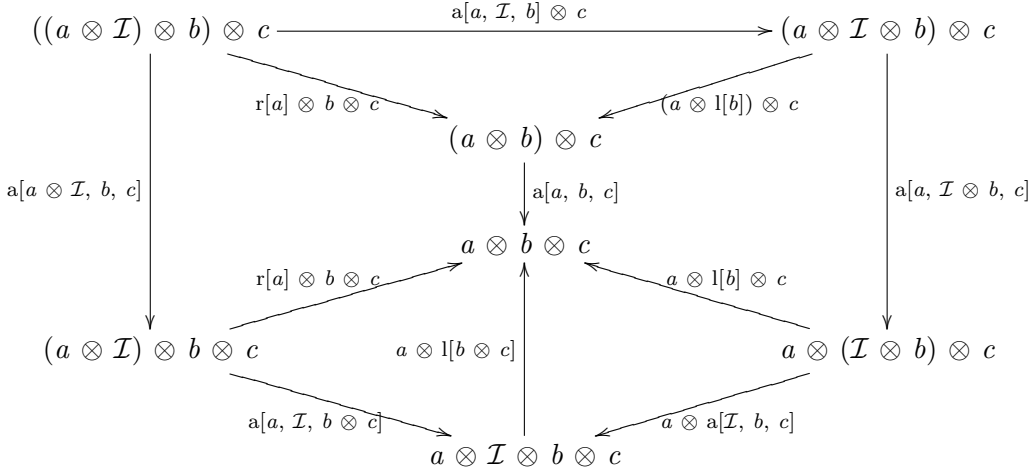
lemma *lunit-tensor-gen*:

assumes *ide a* **and** *ide b* **and** *ide c*

shows $(a \otimes l[b \otimes c]) \cdot (a \otimes a[\mathcal{I}, b, c]) = a \otimes l[b] \otimes c$

proof –

We show that the lower right triangle in the following diagram commutes.



have $((a \otimes l[b \otimes c]) \cdot (a \otimes a[\mathcal{I}, b, c])) \cdot (a[a, \mathcal{I} \otimes b, c] \cdot (a[a, \mathcal{I}, b] \otimes c)) =$
 $((a \otimes l[b \otimes c]) \cdot a[a, \mathcal{I}, b \otimes c]) \cdot a[a \otimes \mathcal{I}, b, c]$

using *assms pentagon comp-assoc* **by** *simp*

also have $\dots = (r[a] \otimes (b \otimes c)) \cdot a[a \otimes \mathcal{I}, b, c]$

using *assms triangle* **by** *auto*

also have $\dots = a[a, b, c] \cdot ((r[a] \otimes b) \otimes c)$

using *assms assoc-naturality [of r[a] b c]* **by** *auto*

also have $\dots = (a[a, b, c] \cdot ((a \otimes l[b]) \otimes c)) \cdot (a[a, \mathcal{I}, b] \otimes c)$

using *assms triangle interchange comp-assoc* **by** *auto*

also have $\dots = (a \otimes (l[b] \otimes c)) \cdot (a[a, \mathcal{I} \otimes b, c] \cdot (a[a, \mathcal{I}, b] \otimes c))$

using *assms assoc-naturality [of a l[b] c]* *comp-assoc* **by** *auto*

finally have $1: ((a \otimes l[b \otimes c]) \cdot (a \otimes a[\mathcal{I}, b, c])) \cdot a[a, \mathcal{I} \otimes b, c] \cdot (a[a, \mathcal{I}, b] \otimes c)$
 $= (a \otimes (l[b] \otimes c)) \cdot a[a, \mathcal{I} \otimes b, c] \cdot (a[a, \mathcal{I}, b] \otimes c)$

by *blast*

The result follows by cancelling the isomorphism $a[a, \mathcal{I} \otimes b, c] \cdot (a[a, \mathcal{I}, b] \otimes c)$

have $2: iso (a[a, \mathcal{I} \otimes b, c] \cdot (a[a, \mathcal{I}, b] \otimes c))$

using *assms isos-compose* **by** *simp*
moreover have
 $seq ((a \otimes l[b \otimes c]) \cdot (a \otimes a[\mathcal{I}, b, c])) (a[a, \mathcal{I} \otimes b, c] \cdot (a[a, \mathcal{I}, b] \otimes c))$
using *assms* **by** *auto*
moreover have $seq (a \otimes (l[b] \otimes c)) (a[a, \mathcal{I} \otimes b, c] \cdot (a[a, \mathcal{I}, b] \otimes c))$
using *assms* **by** *auto*
ultimately show *?thesis*
using *1 2 assms iso-is-retraction retraction-is-epi*
epi-cancel
 $[of\ a[a, \mathcal{I} \otimes b, c] \cdot (a[a, \mathcal{I}, b] \otimes c)$
 $(a \otimes l[b \otimes c]) \cdot (a \otimes a[\mathcal{I}, b, c])\ a \otimes l[b] \otimes c]$
by *auto*
qed

The following result is quoted without proof as Theorem 7 of [3] where it is attributed to MacLane [4]. It also appears as [5], Exercise 1, page 161. I did not succeed within a few hours to construct a proof following MacLane's hint. The proof below is based on [2], Proposition 2.2.4.

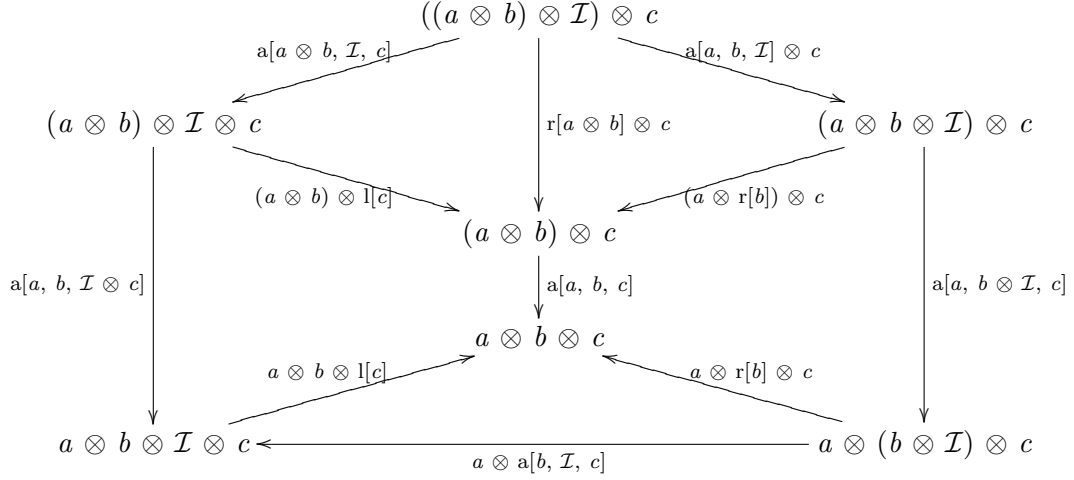
lemma *lunit-tensor'*:
assumes *ide a* **and** *ide b*
shows $l[a \otimes b] \cdot a[\mathcal{I}, a, b] = l[a] \otimes b$
proof –
have $\mathcal{I} \otimes (l[a \otimes b] \cdot a[\mathcal{I}, a, b]) = \mathcal{I} \otimes (l[a] \otimes b)$
using *assms interchange [of \mathcal{I} \mathcal{I}] lunit-tensor-gen* **by** *simp*
moreover have *par* $(l[a \otimes b] \cdot a[\mathcal{I}, a, b])\ (l[a] \otimes b)$
using *assms* **by** *simp*
ultimately show *?thesis*
using *assms L.is-faithful [of $l[a \otimes b] \cdot a[\mathcal{I}, a, b]\ l[a] \otimes b$]* **by** *simp*
qed

lemma *lunit-tensor*:
assumes *ide a* **and** *ide b*
shows $l[a \otimes b] = (l[a] \otimes b) \cdot a^{-1}[\mathcal{I}, a, b]$
using *assms lunit-tensor' invert-side-of-triangle* **by** *simp*

We next show the corresponding result for the right unitor.

lemma *runit-tensor-gen*:
assumes *ide a* **and** *ide b* **and** *ide c*
shows $r[a \otimes b] \otimes c = ((a \otimes r[b]) \otimes c) \cdot (a[a, b, \mathcal{I}] \otimes c)$
proof –

We show that the upper right triangle in the following diagram commutes.



have $r[a \otimes b] \otimes c = ((a \otimes b) \otimes l[c]) \cdot a[a \otimes b, \mathcal{I}, c]$
using *assms triangle by simp*
also have $\dots = (a^{-1}[a, b, c] \cdot (a \otimes b \otimes l[c]) \cdot a[a, b, \mathcal{I} \otimes c]) \cdot a[a \otimes b, \mathcal{I}, c]$
using *assms assoc-naturality [of a b l[c]] comp-arr-dom comp-cod-arr invert-side-of-triangle(1)*
by force
also have $\dots = a^{-1}[a, b, c] \cdot (a \otimes b \otimes l[c]) \cdot a[a, b, \mathcal{I} \otimes c] \cdot a[a \otimes b, \mathcal{I}, c]$
using *comp-assoc by force*
also have $\dots = a^{-1}[a, b, c] \cdot ((a \otimes (r[b] \otimes c)) \cdot (a \otimes a^{-1}[b, \mathcal{I}, c])) \cdot a[a, b, \mathcal{I} \otimes c] \cdot a[a \otimes b, \mathcal{I}, c]$
using *assms triangle [of b c] interchange invert-side-of-triangle(2) by force*
also have $\dots = (((a \otimes r[b]) \otimes c) \cdot a^{-1}[a, b \otimes \mathcal{I}, c]) \cdot (a \otimes a^{-1}[b, \mathcal{I}, c]) \cdot a[a, b, \mathcal{I} \otimes c] \cdot a[a \otimes b, \mathcal{I}, c]$
using *assms assoc'-naturality [of a r[b] c] comp-assoc by force*
also have $\dots = ((a \otimes r[b]) \otimes c) \cdot a^{-1}[a, b \otimes \mathcal{I}, c] \cdot (a \otimes a^{-1}[b, \mathcal{I}, c]) \cdot a[a, b, \mathcal{I} \otimes c] \cdot a[a \otimes b, \mathcal{I}, c]$
using *comp-assoc by simp*
also have $\dots = ((a \otimes r[b]) \otimes c) \cdot (a[a, b, \mathcal{I}] \otimes c)$
using *assms pentagon invert-side-of-triangle(1) invert-side-of-triangle(1)*
 $[of a[a, b, \mathcal{I} \otimes c] \cdot a[a \otimes b, \mathcal{I}, c] \ a \otimes a[b, \mathcal{I}, c] \ a[a, b \otimes \mathcal{I}, c] \cdot (a[a, b, \mathcal{I}] \otimes c)]$
by force
finally show *?thesis by blast*
qed

lemma *runit-tensor*:
assumes *ide a and ide b*
shows $r[a \otimes b] = (a \otimes r[b]) \cdot a[a, b, \mathcal{I}]$
proof –
have $((a \otimes r[b]) \cdot a[a, b, \mathcal{I}]) \otimes \mathcal{I} = r[a \otimes b] \otimes \mathcal{I}$

using *assms interchange* [of $\mathcal{I} \mathcal{I}$] *runit-tensor-gen* **by** *simp*
moreover have *par* $((a \otimes r[b]) \cdot a[a, b, \mathcal{I}]) r[a \otimes b]$
using *assms* **by** *simp*
ultimately show *?thesis*
using *assms R.is-faithful* [of $(a \otimes r[b]) \cdot (a[a, b, \mathcal{I}]) r[a \otimes b]$]
by *fastforce*
qed

lemma *runit-tensor'*:
assumes *ide a* **and** *ide b*
shows $r[a \otimes b] \cdot a^{-1}[a, b, \mathcal{I}] = a \otimes r[b]$
using *assms runit-tensor invert-side-of-triangle* **by** *force*

Sometimes inverted forms of the triangle and pentagon axioms are useful.

lemma *triangle'*:
assumes *ide a* **and** *ide b*
shows $(a \otimes l[b]) = (r[a] \otimes b) \cdot a^{-1}[a, \mathcal{I}, b]$
proof –
have $(r[a] \otimes b) \cdot a^{-1}[a, \mathcal{I}, b] = ((a \otimes l[b]) \cdot a[a, \mathcal{I}, b]) \cdot a^{-1}[a, \mathcal{I}, b]$
using *assms triangle* **by** *auto*
also have $\dots = (a \otimes l[b])$
using *assms comp-arr-dom comp-assoc* **by** *auto*
finally show *?thesis* **by** *auto*
qed

lemma *pentagon'*:
assumes *ide a* **and** *ide b* **and** *ide c* **and** *ide d*
shows $((a^{-1}[a, b, c] \otimes d) \cdot a^{-1}[a, b \otimes c, d]) \cdot (a \otimes a^{-1}[b, c, d])$
 $= a^{-1}[a \otimes b, c, d] \cdot a^{-1}[a, b, c \otimes d]$
proof –
have $((a^{-1}[a, b, c] \otimes d) \cdot a^{-1}[a, b \otimes c, d]) \cdot (a \otimes a^{-1}[b, c, d])$
 $= \text{inv} ((a \otimes a[b, c, d]) \cdot (a[a, b \otimes c, d] \cdot (a[a, b, c] \otimes d)))$
using *assms isos-compose inv-comp* **by** *simp*
also have $\dots = \text{inv} (a[a, b, c \otimes d] \cdot a[a \otimes b, c, d])$
using *assms pentagon* **by** *auto*
also have $\dots = a^{-1}[a \otimes b, c, d] \cdot a^{-1}[a, b, c \otimes d]$
using *assms inv-comp* **by** *simp*
finally show *?thesis* **by** *auto*
qed

The following non-obvious fact is Corollary 2.2.5 from [2]. The statement that $l[\mathcal{I}] = r[\mathcal{I}]$ is Theorem 6 from [3]. MacLane [5] does not show this, but assumes it as an axiom.

lemma *unitor-coincidence*:
shows $l[\mathcal{I}] = \iota$ **and** $r[\mathcal{I}] = \iota$
proof –
have $l[\mathcal{I}] \otimes \mathcal{I} = (\mathcal{I} \otimes l[\mathcal{I}]) \cdot a[\mathcal{I}, \mathcal{I}, \mathcal{I}]$
using *lunit-tensor'* [of $\mathcal{I} \mathcal{I}$] *lunit-commutes-with-L* [of \mathcal{I}] **by** *simp*
moreover have $r[\mathcal{I}] \otimes \mathcal{I} = (\mathcal{I} \otimes r[\mathcal{I}]) \cdot a[\mathcal{I}, \mathcal{I}, \mathcal{I}]$
using *triangle* [of $\mathcal{I} \mathcal{I}$] **by** *simp*

moreover have $\iota \otimes \mathcal{I} = (\mathcal{I} \otimes l[\mathcal{I}]) \cdot a[\mathcal{I}, \mathcal{I}, \mathcal{I}]$
using *lunit-char comp-arr-dom unit-in-hom comp-assoc* **by auto**
ultimately have $l[\mathcal{I}] \otimes \mathcal{I} = \iota \otimes \mathcal{I} \wedge r[\mathcal{I}] \otimes \mathcal{I} = \iota \otimes \mathcal{I}$
by argo
moreover have $\text{par } l[\mathcal{I}] \iota \wedge \text{par } r[\mathcal{I}] \iota$
using *unit-in-hom* **by force**
ultimately have $1: l[\mathcal{I}] = \iota \wedge r[\mathcal{I}] = \iota$
using *R.is-faithful* **by metis**
show $l[\mathcal{I}] = \iota$ **using** 1 **by auto**
show $r[\mathcal{I}] = \iota$ **using** 1 **by auto**
qed

lemma *unit-triangle*:
shows $\iota \otimes \mathcal{I} = (\mathcal{I} \otimes \iota) \cdot a[\mathcal{I}, \mathcal{I}, \mathcal{I}]$
and $(\iota \otimes \mathcal{I}) \cdot a^{-1}[\mathcal{I}, \mathcal{I}, \mathcal{I}] = \mathcal{I} \otimes \iota$
using *triangle [of \mathcal{I} \mathcal{I}] triangle' [of \mathcal{I} \mathcal{I}] unitor-coincidence* **by auto**

The only isomorphism that commutes with ι is \mathcal{I} .

lemma *iso-commuting-with-unit-equals-unity*:
assumes $\langle f : \mathcal{I} \rightarrow \mathcal{I} \rangle$ **and** *iso f* **and** $f \cdot \iota = \iota \cdot (f \otimes f)$
shows $f = \mathcal{I}$
proof –
have $\mathcal{I} \otimes f = \mathcal{I} \otimes \mathcal{I}$
proof –
have $f \otimes f = f \otimes \mathcal{I}$
by (*metis assms(1,3) iso-cancel-left runit-naturality seqE seqI' unit-in-hom-ax unit-is-iso unitor-coincidence(2)*)
thus *?thesis*
by (*metis assms(1–2) R.preserves-comp comp-cod-arr comp-inv-arr' ideD(1) ide-unity in-homE interchange*)
qed
moreover have $\text{par } f \mathcal{I}$
using *assms* **by auto**
ultimately show $f = \mathcal{I}$
using *L.is-faithful* **by metis**
qed

end

We now show that the unit ι of a monoidal category is unique up to a unique isomorphism (Proposition 2.2.6 of [2]).

locale *monoidal-category-with-alternate-unit* =
monoidal-category C T α ι +
 C_1 : *monoidal-category* C T α ι_1
for $C :: 'a \text{ comp}$ (**infixr** $\langle \cdot \rangle$ 55)
and $T :: 'a * 'a \Rightarrow 'a$
and $\alpha :: 'a * 'a * 'a \Rightarrow 'a$
and $\iota :: 'a$
and $\iota_1 :: 'a$

begin

no-notation $C_1.tensor$ (**infix** $\langle \otimes \rangle$ 53)
no-notation $C_1.unity$ ($\langle \mathcal{I} \rangle$)
no-notation $C_1.lunit$ ($\langle l[-] \rangle$)
no-notation $C_1.runit$ ($\langle r[-] \rangle$)
no-notation $C_1.assoc$ ($\langle a[-, -, -] \rangle$)
no-notation $C_1.assoc'$ ($\langle a^{-1}[-, -, -] \rangle$)

notation $C_1.tensor$ (**infix** $\langle \otimes_1 \rangle$ 53)
notation $C_1.unity$ ($\langle \mathcal{I}_1 \rangle$)
notation $C_1.lunit$ ($\langle l_1[-] \rangle$)
notation $C_1.runit$ ($\langle r_1[-] \rangle$)
notation $C_1.assoc$ ($\langle a_1[-, -, -] \rangle$)
notation $C_1.assoc'$ ($\langle a_1^{-1}[-, -, -] \rangle$)

definition i

where $i \equiv l[\mathcal{I}_1] \cdot inv\ r_1[\mathcal{I}]$

lemma $iso-i$:

shows $\langle i : \mathcal{I} \rightarrow \mathcal{I}_1 \rangle$ **and** $iso\ i$

proof –

show $\langle i : \mathcal{I} \rightarrow \mathcal{I}_1 \rangle$

using $C_1.iso-runit\ inv-in-hom\ i-def$ **by** $auto$

show $iso\ i$

using $iso-lunit\ C_1.iso-runit\ isos-compose\ i-def$ **by** $simp$

qed

The following is Exercise 2.2.7 of [2].

lemma $i-maps-\iota-to-\iota_1$:

shows $i \cdot \iota = \iota_1 \cdot (i \otimes i)$

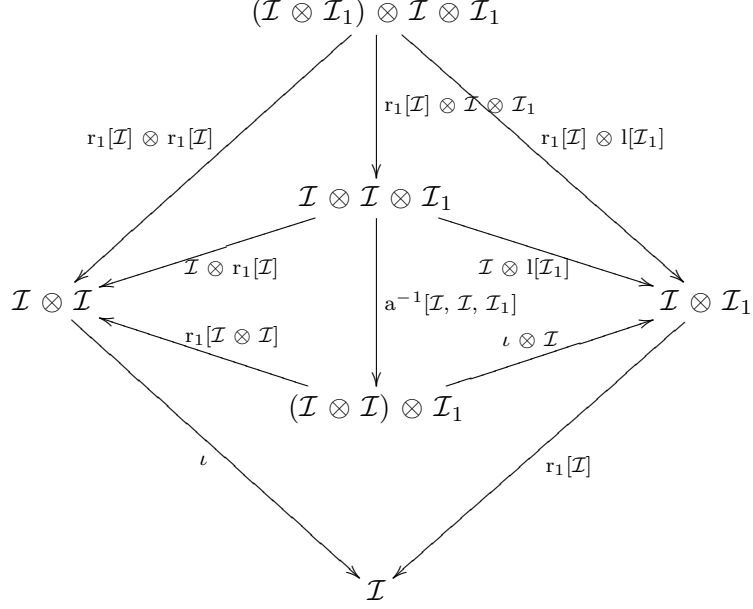
proof –

have $1: inv\ r_1[\mathcal{I}] \cdot \iota = (r_1[\mathcal{I}] \otimes l[\mathcal{I}_1]) \cdot (inv\ r_1[\mathcal{I}] \otimes inv\ r_1[\mathcal{I}])$

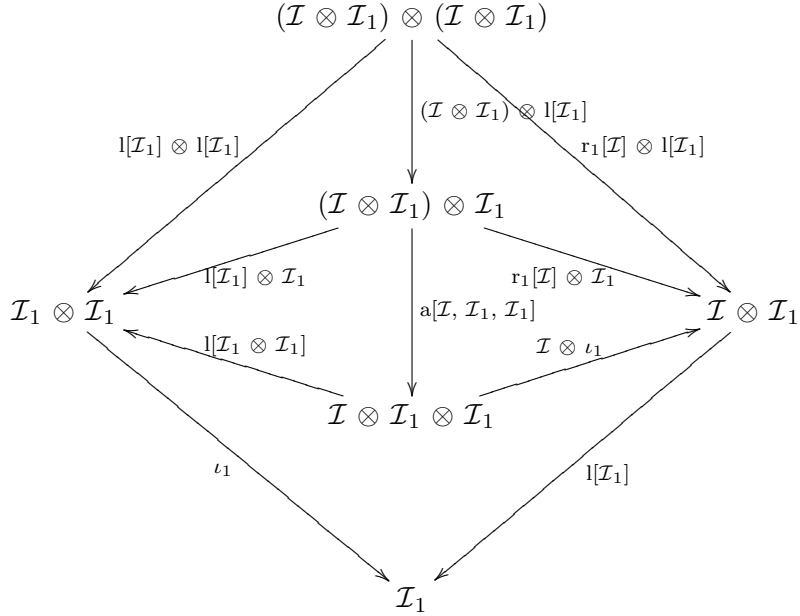
proof –

have $\iota \cdot (r_1[\mathcal{I}] \otimes r_1[\mathcal{I}]) = r_1[\mathcal{I}] \cdot (r_1[\mathcal{I}] \otimes l[\mathcal{I}_1])$

proof –

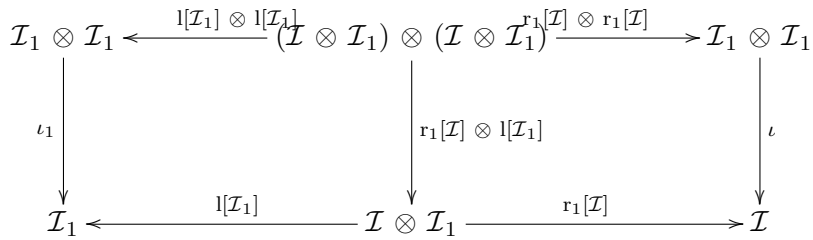


have $\iota \cdot (r_1[\mathcal{I}] \otimes r_1[\mathcal{I}]) = \iota \cdot (\mathcal{I} \otimes r_1[\mathcal{I}]) \cdot (r_1[\mathcal{I}] \otimes \mathcal{I} \otimes \mathcal{I}_1)$
 using *interchange comp-cod-arr comp-arr-dom* by *simp*
 also have $\dots = \iota \cdot (r_1[\mathcal{I} \otimes \mathcal{I}] \cdot a^{-1}[\mathcal{I}, \mathcal{I}, \mathcal{I}_1]) \cdot (r_1[\mathcal{I}] \otimes \mathcal{I} \otimes \mathcal{I}_1)$
 using $C_1.runit-tensor'$ by *auto*
 also have $\dots = (\iota \cdot r_1[\mathcal{I} \otimes \mathcal{I}]) \cdot a^{-1}[\mathcal{I}, \mathcal{I}, \mathcal{I}_1] \cdot (r_1[\mathcal{I}] \otimes \mathcal{I} \otimes \mathcal{I}_1)$
 using *comp-assoc* by *auto*
 also have $\dots = (r_1[\mathcal{I}] \cdot (\iota \otimes \mathcal{I}_1)) \cdot a^{-1}[\mathcal{I}, \mathcal{I}, \mathcal{I}_1] \cdot (r_1[\mathcal{I}] \otimes \mathcal{I} \otimes \mathcal{I}_1)$
 using $C_1.runit-naturality$ [of ι] *unit-in-hom* by *fastforce*
 also have $\dots = r_1[\mathcal{I}] \cdot ((\iota \otimes \mathcal{I}_1) \cdot a^{-1}[\mathcal{I}, \mathcal{I}, \mathcal{I}_1]) \cdot (r_1[\mathcal{I}] \otimes \mathcal{I} \otimes \mathcal{I}_1)$
 using *comp-assoc* by *auto*
 also have $\dots = r_1[\mathcal{I}] \cdot (\mathcal{I} \otimes l[\mathcal{I}_1]) \cdot (r_1[\mathcal{I}] \otimes \mathcal{I} \otimes \mathcal{I}_1)$
 using *lunit-tensor lunit-commutes-with-L unitor-coincidence* by *simp*
 also have $\dots = r_1[\mathcal{I}] \cdot (r_1[\mathcal{I}] \otimes l[\mathcal{I}_1])$
 using *interchange comp-arr-dom comp-cod-arr* by *simp*
 finally show *?thesis* by *blast*
 qed
 moreover have $seq \iota (r_1[\mathcal{I}] \otimes r_1[\mathcal{I}]) \wedge seq r_1[\mathcal{I}] (r_1[\mathcal{I}] \otimes l[\mathcal{I}_1])$
 using *unit-in-hom* by *fastforce*
 moreover have $iso r_1[\mathcal{I}] \wedge iso (r_1[\mathcal{I}] \otimes r_1[\mathcal{I}])$
 using $C_1.iso-runit$ *tensor-preserves-iso* by *force*
 ultimately show *?thesis*
 using *invert-opposite-sides-of-square inv-tensor* by *metis*
 qed
 have $2: l[\mathcal{I}_1] \cdot (r_1[\mathcal{I}] \otimes l[\mathcal{I}_1]) = \iota_1 \cdot (l[\mathcal{I}_1] \otimes l[\mathcal{I}_1])$
 proof –



have $l[\mathcal{I}_1] \cdot (r_1[\mathcal{I}] \otimes l[\mathcal{I}_1]) = l[\mathcal{I}_1] \cdot (r_1[\mathcal{I}] \otimes \mathcal{I}_1) \cdot ((\mathcal{I} \otimes \mathcal{I}_1) \otimes l[\mathcal{I}_1])$
 using *interchange comp-arr-dom comp-cod-arr* **by force**
 also have $\dots = l[\mathcal{I}_1] \cdot ((\mathcal{I} \otimes \iota_1) \cdot a[\mathcal{I}, \mathcal{I}_1, \mathcal{I}_1]) \cdot ((\mathcal{I} \otimes \mathcal{I}_1) \otimes l[\mathcal{I}_1])$
 using $C_1.runit-tensor$ $C_1.unitor-coincidence$ $C_1.runit-commutes-with-R$ **by simp**
 also have $\dots = (l[\mathcal{I}_1] \cdot (\mathcal{I} \otimes \iota_1)) \cdot a[\mathcal{I}, \mathcal{I}_1, \mathcal{I}_1] \cdot ((\mathcal{I} \otimes \mathcal{I}_1) \otimes l[\mathcal{I}_1])$
 using *comp-assoc* **by fastforce**
 also have $\dots = (\iota_1 \cdot l[\mathcal{I}_1 \otimes \mathcal{I}_1]) \cdot a[\mathcal{I}, \mathcal{I}_1, \mathcal{I}_1] \cdot ((\mathcal{I} \otimes \mathcal{I}_1) \otimes l[\mathcal{I}_1])$
 using *lunit-naturality* [of ι_1] $C_1.unitor-in-hom$ *lunit-commutes-with-L* **by fastforce**
 also have $\dots = \iota_1 \cdot (l[\mathcal{I}_1 \otimes \mathcal{I}_1] \cdot a[\mathcal{I}, \mathcal{I}_1, \mathcal{I}_1]) \cdot ((\mathcal{I} \otimes \mathcal{I}_1) \otimes l[\mathcal{I}_1])$
 using *comp-assoc* **by force**
 also have $\dots = \iota_1 \cdot (l[\mathcal{I}_1] \otimes \mathcal{I}_1) \cdot ((\mathcal{I} \otimes \mathcal{I}_1) \otimes l[\mathcal{I}_1])$
 using *lunit-tensor'* **by auto**
 also have $\dots = \iota_1 \cdot (l[\mathcal{I}_1] \otimes l[\mathcal{I}_1])$
 using *interchange comp-arr-dom comp-cod-arr* **by simp**
 finally show *?thesis* **by blast**

qed
 show *?thesis*
 proof –



have $i \cdot \iota = l[\mathcal{I}_1] \cdot inv\ r_1[\mathcal{I}] \cdot \iota$

using *i-def comp-assoc* by *auto*
 also have ... = $(l[\mathcal{I}_1] \cdot (r_1[\mathcal{I}] \otimes l[\mathcal{I}_1])) \cdot (inv\ r_1[\mathcal{I}] \otimes inv\ r_1[\mathcal{I}])$
 using *1 comp-assoc* by *simp*
 also have ... = $\iota_1 \cdot (l[\mathcal{I}_1] \otimes l[\mathcal{I}_1]) \cdot (inv\ r_1[\mathcal{I}] \otimes inv\ r_1[\mathcal{I}])$
 using *2 comp-assoc* by *fastforce*
 also have ... = $\iota_1 \cdot (i \otimes i)$
 using *interchange i-def* by *simp*
 finally show *?thesis* by *blast*
 qed
 qed

lemma *inv-i-iso-ι*:

assumes « $f : \mathcal{I} \rightarrow \mathcal{I}_1$ » and *iso* f and $f \cdot \iota = \iota_1 \cdot (f \otimes f)$

shows « $inv\ i \cdot f : \mathcal{I} \rightarrow \mathcal{I}$ » and *iso* $(inv\ i \cdot f)$

and $(inv\ i \cdot f) \cdot \iota = \iota \cdot (inv\ i \cdot f \otimes inv\ i \cdot f)$

proof –

show 1: « $inv\ i \cdot f : \mathcal{I} \rightarrow \mathcal{I}$ »

using *assms iso-i inv-in-hom* by *blast*

show *iso* $(inv\ i \cdot f)$

using *assms 1 iso-i inv-in-hom*

by (*intro isos-compose, auto*)

show $(inv\ i \cdot f) \cdot \iota = \iota \cdot (inv\ i \cdot f \otimes inv\ i \cdot f)$

proof –

have $(inv\ i \cdot f) \cdot \iota = (inv\ i \cdot \iota_1) \cdot (f \otimes f)$

using *assms iso-i comp-assoc* by *auto*

also have ... = $(\iota \cdot (inv\ i \otimes inv\ i)) \cdot (f \otimes f)$

by (*metis unit-in-hom-ax i-maps-ι-to-ι₁ invert-opposite-sides-of-square iso-i inv-tensor tensor-preserves-iso seqI'*)

also have ... = $\iota \cdot (inv\ i \cdot f \otimes inv\ i \cdot f)$

using *assms 1 iso-i interchange comp-assoc* by *fastforce*

finally show *?thesis* by *blast*

qed

qed

lemma *unit-unique-upto-unique-iso*:

shows $\exists! f. \langle f : \mathcal{I} \rightarrow \mathcal{I}_1 \rangle \wedge iso\ f \wedge f \cdot \iota = \iota_1 \cdot (f \otimes f)$

proof

show « $i : \mathcal{I} \rightarrow \mathcal{I}_1$ » $\wedge iso\ i \wedge i \cdot \iota = \iota_1 \cdot (i \otimes i)$

using *iso-i i-maps-ι-to-ι₁* by *auto*

show $\bigwedge f. \langle f : \mathcal{I} \rightarrow \mathcal{I}_1 \rangle \wedge iso\ f \wedge f \cdot \iota = \iota_1 \cdot (f \otimes f) \implies f = i$

proof –

fix f

assume $f: \langle f : \mathcal{I} \rightarrow \mathcal{I}_1 \rangle \wedge iso\ f \wedge f \cdot \iota = \iota_1 \cdot (f \otimes f)$

have $inv\ i \cdot f = i$

using *f inv-i-iso-ι iso-commuting-with-unit-equals-unity* by *blast*

hence *ide* $(C\ (inv\ i)\ f)$

using *iso-i* by *simp*

thus $f = i$

using *section-retraction-of-iso(2)* [*of inv i f*] *inverse-arrow-unique inv-is-inverse*

```

      iso-i
    by blast
  qed
qed

end

```

2.2 Elementary Monoidal Category

Although the economy of data assumed by *monoidal-category* is useful for general results, to establish interpretations it is more convenient to work with a traditional definition of monoidal category. The following locale provides such a definition. It permits a monoidal category to be specified by giving the tensor product and the components of the associator and unitors, which are required only to satisfy elementary conditions that imply functoriality and naturality, without having to worry about extensionality or formal interpretations for the various functors and natural transformations.

```

locale elementary-monoidal-category =
  category C
for C :: 'a comp      (infixr ⟨⟩ 55)
and tensor :: 'a ⇒ 'a ⇒ 'a      (infixr ⟨⊗⟩ 53)
and unity :: 'a          (⟨I⟩)
and lunit :: 'a ⇒ 'a      (⟨l[-]⟩)
and runit :: 'a ⇒ 'a      (⟨r[-]⟩)
and assoc :: 'a ⇒ 'a ⇒ 'a ⇒ 'a (⟨a[-, -, -]⟩) +
assumes ide-unity [simp]: ide I
and iso-lunit: ide a ⇒ iso l[a]
and iso-runit: ide a ⇒ iso r[a]
and iso-assoc: [[ ide a; ide b; ide c ] ⇒ iso a[a, b, c]
and tensor-in-hom [simp]: [[ ⟨f : a → b⟩; ⟨g : c → d⟩ ] ⇒ ⟨f ⊗ g : a ⊗ c → b ⊗ d⟩
and tensor-preserves-ide: [[ ide a; ide b ] ⇒ ide (a ⊗ b)
and interchange: [[ seq g f; seq g' f' ] ⇒ (g ⊗ g') · (f ⊗ f') = g · f ⊗ g' · f'
and lunit-in-hom [simp]: ide a ⇒ ⟨l[a] : I ⊗ a → a⟩
and lunit-naturality: arr f ⇒ l[cod f] · (I ⊗ f) = f · l[dom f]
and runit-in-hom [simp]: ide a ⇒ ⟨r[a] : a ⊗ I → a⟩
and runit-naturality: arr f ⇒ r[cod f] · (f ⊗ I) = f · r[dom f]
and assoc-in-hom [simp]:
  [[ ide a; ide b; ide c ] ⇒ ⟨a[a, b, c] : (a ⊗ b) ⊗ c → a ⊗ b ⊗ c⟩
and assoc-naturality:
  [[ arr f0; arr f1; arr f2 ] ⇒ a[cod f0, cod f1, cod f2] · ((f0 ⊗ f1) ⊗ f2)
    = (f0 ⊗ (f1 ⊗ f2)) · a[dom f0, dom f1, dom f2]
and triangle: [[ ide a; ide b ] ⇒ (a ⊗ l[b]) · a[a, I, b] = r[a] ⊗ b
and pentagon: [[ ide a; ide b; ide c; ide d ] ⇒
  (a ⊗ a[b, c, d]) · a[a, b ⊗ c, d] · (a[a, b, c] ⊗ d)
    = a[a, b, c ⊗ d] · a[a ⊗ b, c, d]

```

An interpretation for the *monoidal-category* locale readily induces an interpretation for the *elementary-monoidal-category* locale.

```

context monoidal-category

```

begin

lemma *induces-elementary-monoidal-category*:

shows *elementary-monoidal-category C tensor I lunit runit assoc*

using *iso-assoc tensor-preserves-ide assoc-in-hom tensor-in-hom*

assoc-naturality lunit-naturality runit-naturality lunit-in-hom runit-in-hom

iso-lunit iso-runit interchange pentagon triangle

by *unfold-locales auto*

end

context *elementary-monoidal-category*

begin

interpretation *CC: product-category C C ..*

interpretation *CCC: product-category C CC.comp ..*

definition *T :: 'a * 'a \Rightarrow 'a*

where *T f \equiv if CC.arr f then (fst f \otimes snd f) else null*

lemma *T-simp [simp]*:

assumes *arr f and arr g*

shows *T (f, g) = f \otimes g*

using *assms T-def by simp*

lemma *arr-tensor [simp]*:

assumes *arr f and arr g*

shows *arr (f \otimes g)*

using *assms tensor-in-hom by blast*

lemma *dom-tensor [simp]*:

assumes *arr f and arr g*

shows *dom (f \otimes g) = dom f \otimes dom g*

using *assms tensor-in-hom by blast*

lemma *cod-tensor [simp]*:

assumes *arr f and arr g*

shows *cod (f \otimes g) = cod f \otimes cod g*

using *assms tensor-in-hom by blast*

interpretation *T: binary-endofunctor C T*

using *interchange T-def*

apply *unfold-locales*

apply *auto[4]*

by *(elim CC.seqE, auto)*

lemma *binary-endofunctor-T:*

shows *binary-endofunctor C T ..*

interpretation *ToTC*: *functor CCC.comp C T.ToTC*
using *T.functor-ToTC* **by** *auto*

interpretation *ToCT*: *functor CCC.comp C T.ToCT*
using *T.functor-ToCT* **by** *auto*

definition α

where $\alpha f \equiv$ *if* *CCC.arr f*
 then $(fst f \otimes (fst (snd f) \otimes snd (snd f))) \cdot$
 $a[dom (fst f), dom (fst (snd f)), dom (snd (snd f))]$
 else *null*

lemma *α -ide-simp* [*simp*]:

assumes *ide a* **and** *ide b* **and** *ide c*

shows $\alpha (a, b, c) = a[a, b, c]$

unfolding *α -def* **using** *assms assoc-in-hom comp-cod-arr*
by (*metis CC.arrIPC CCC.arrIPC fst-conv ide-char in-homE snd-conv*)

lemma *arr-assoc* [*simp*]:

assumes *ide a* **and** *ide b* **and** *ide c*

shows *arr* $a[a, b, c]$

using *assms assoc-in-hom* **by** *blast*

lemma *dom-assoc* [*simp*]:

assumes *ide a* **and** *ide b* **and** *ide c*

shows *dom* $a[a, b, c] = (a \otimes b) \otimes c$

using *assms assoc-in-hom* **by** *blast*

lemma *cod-assoc* [*simp*]:

assumes *ide a* **and** *ide b* **and** *ide c*

shows *cod* $a[a, b, c] = a \otimes b \otimes c$

using *assms assoc-in-hom* **by** *blast*

interpretation α : *natural-isomorphism CCC.comp C T.ToTC T.ToCT* α

proof –

interpret α : *transformation-by-components CCC.comp C T.ToTC T.ToCT* α

apply *unfold-locales*

unfolding *α -def T.ToTC-def T.ToCT-def T-def*

using *comp-arr-dom comp-cod-arr assoc-naturality*

by *simp-all*

interpret α : *natural-isomorphism CCC.comp C T.ToTC T.ToCT* α .*map*

using *iso-assoc α .map-simp-ide assoc-in-hom tensor-preserves-ide α -def*

by (*unfold-locales, auto*)

have $\alpha = \alpha$.*map*

using *assoc-naturality α -def comp-cod-arr T.ToTC-def T-def α .map-def* **by** *auto*

thus *natural-isomorphism CCC.comp C T.ToTC T.ToCT* α

using *α .natural-isomorphism-axioms* **by** *simp*

qed

interpretation α' : *inverse-transformation* $CCC.comp\ C\ T.ToTC\ T.ToCT\ \alpha\ ..$

interpretation L : *functor* $C\ C\ \langle\lambda f. T\ (\mathcal{I}, f)\rangle$
using $T.fixing-ide-gives-functor-1$ **by** *auto*

interpretation R : *functor* $C\ C\ \langle\lambda f. T\ (f, \mathcal{I})\rangle$
using $T.fixing-ide-gives-functor-2$ **by** *auto*

interpretation l : *natural-isomorphism* $C\ C\ \langle\lambda f. T\ (\mathcal{I}, f)\rangle\ map$
 $\langle\lambda f. if\ arr\ f\ then\ f \cdot l[dom\ f]\ else\ null\rangle$

proof –

interpret l : *transformation-by-components* $C\ C\ \langle\lambda f. T\ (\mathcal{I}, f)\rangle\ map\ \langle\lambda a. l[a]\rangle$
using $lunit-naturality$ **by** $(unfold-locales, auto)$

interpret l : *natural-isomorphism* $C\ C\ \langle\lambda f. T\ (\mathcal{I}, f)\rangle\ map\ l.map$
using $iso-lunit$ **by** $(unfold-locales, simp)$

have $l.map = (\lambda f. if\ arr\ f\ then\ f \cdot l[dom\ f]\ else\ null)$

using $l.map-def\ lunit-naturality$ **by** *fastforce*

thus *natural-isomorphism* $C\ C\ (\lambda f. T\ (\mathcal{I}, f))\ map\ (\lambda f. if\ arr\ f\ then\ f \cdot l[dom\ f]\ else\ null)$
using $l.natural-isomorphism-axioms$ **by** *force*

qed

interpretation q : *natural-isomorphism* $C\ C\ \langle\lambda f. T\ (f, \mathcal{I})\rangle\ map$
 $\langle\lambda f. if\ arr\ f\ then\ f \cdot r[dom\ f]\ else\ null\rangle$

proof –

interpret q : *transformation-by-components* $C\ C\ \langle\lambda f. T\ (f, \mathcal{I})\rangle\ map\ \langle\lambda a. r[a]\rangle$
using $runit-naturality$ **by** $(unfold-locales, auto)$

interpret q : *natural-isomorphism* $C\ C\ \langle\lambda f. T\ (f, \mathcal{I})\rangle\ map\ q.map$
using $iso-runit\ q.map-simp-ide$ **by** $(unfold-locales, simp)$

have $(\lambda f. if\ arr\ f\ then\ f \cdot r[dom\ f]\ else\ null) = q.map$

using $q.map-def\ runit-naturality\ T-simp$ **by** *fastforce*

thus *natural-isomorphism* $C\ C\ (\lambda f. T\ (f, \mathcal{I}))\ map\ (\lambda f. if\ arr\ f\ then\ f \cdot r[dom\ f]\ else\ null)$
using $q.natural-isomorphism-axioms$ **by** *force*

qed

The endofunctors $\lambda f. T\ (\mathcal{I}, f)$ and $\lambda f. T\ (f, \mathcal{I})$ are equivalence functors, due to the existence of the unitors.

interpretation L : *equivalence-functor* $C\ C\ \langle\lambda f. T\ (\mathcal{I}, f)\rangle$

proof –

interpret *endofunctor* $C\ \langle\lambda f. T\ (\mathcal{I}, f)\rangle\ ..$

show *equivalence-functor* $C\ C\ (\lambda f. T\ (\mathcal{I}, f))$

using $isomorphic-to-identity-is-equivalence\ l.natural-isomorphism-axioms$ **by** *simp*

qed

interpretation R : *equivalence-functor* $C\ C\ \langle\lambda f. T\ (f, \mathcal{I})\rangle$

proof –

interpret *endofunctor* $C\ \langle\lambda f. T\ (f, \mathcal{I})\rangle\ ..$

show *equivalence-functor* $C\ C\ (\lambda f. T\ (f, \mathcal{I}))$

using $isomorphic-to-identity-is-equivalence\ q.natural-isomorphism-axioms$ **by** *simp*

qed

To complete an interpretation of the *monoidal-category* locale, we define $\iota \equiv 1[\mathcal{I}]$. We could also have chosen $\iota \equiv \varrho[\mathcal{I}]$ as the two are equal, though to prove that requires some work yet.

definition ι
where $\iota \equiv 1[\mathcal{I}]$

lemma *ι -in-hom*:
shows $\langle \iota : \mathcal{I} \otimes \mathcal{I} \rightarrow \mathcal{I} \rangle$
using *lunit-in-hom ι -def* **by** *simp*

lemma *induces-monoidal-category*:
shows *monoidal-category* $C T \alpha \iota$

proof –

have *1*: $\langle \iota : \mathcal{I} \otimes \mathcal{I} \rightarrow \mathcal{I} \rangle$
using *lunit-in-hom ι -def* **by** *simp*

interpret *L*: *equivalence-functor* $C C \langle \lambda f. T (cod \iota, f) \rangle$

proof –

have $(\lambda f. T (\mathcal{I}, f)) = (\lambda f. T (cod \iota, f))$ **using** *1* **by** *fastforce*
thus *equivalence-functor* $C C (\lambda f. T (cod \iota, f))$

using *L.equivalence-functor-axioms T-def* **by** *simp*

qed

interpret *R*: *equivalence-functor* $C C \langle \lambda f. T (f, cod \iota) \rangle$

proof –

have $(\lambda f. T (f, \mathcal{I})) = (\lambda f. T (f, cod \iota))$ **using** *1* **by** *fastforce*
thus *equivalence-functor* $C C (\lambda f. T (f, cod \iota))$

using *R.equivalence-functor-axioms T-def* **by** *simp*

qed

show *?thesis*

proof

show $\langle \iota : T (cod \iota, cod \iota) \rightarrow cod \iota \rangle$ **using** *1* **by** *fastforce*

show *iso ι* **using** *iso-lunit ι -def* **by** *simp*

show $\bigwedge a b c d. \llbracket ide a; ide b; ide c; ide d \rrbracket \implies$

$$T (a, \alpha (b, c, d)) \cdot \alpha (a, T (b, c), d) \cdot T (\alpha (a, b, c), d) \\ = \alpha (a, b, T (c, d)) \cdot \alpha (T (a, b), c, d)$$

using *pentagon tensor-preserves-ide* **by** *simp*

qed

qed

interpretation *MC*: *monoidal-category* $C T \alpha \iota$
using *induces-monoidal-category* **by** *auto*

We now show that the notions defined in the interpretation *MC* agree with their counterparts in the present locale. These facts are needed if we define an interpretation for the *elementary-monoidal-category* locale, use it to obtain the induced interpretation for *monoidal-category*, and then want to transfer facts obtained in the induced interpretation back to the original one.

lemma *\mathcal{I} -agreement*:
shows *MC.unity* = \mathcal{I}

by (*metis* ι -def ide-unity in-homE lunit-in-hom)

lemma *L-agreement*:

shows $MC.L = (\lambda f. T (\mathcal{I}, f))$

using ι -in-hom **by** *auto*

lemma *R-agreement*:

shows $MC.R = (\lambda f. T (f, \mathcal{I}))$

using ι -in-hom **by** *auto*

We wish to show that the components of the unitors $MC.l$ and $MC.r$ defined in the induced interpretation MC agree with those given by the parameters $lunit$ and $runit$ to the present locale. To avoid a lengthy development that repeats work already done in the *monoidal-category* locale, we establish the agreement in a special case and then use the properties already shown for MC to prove the general case. In particular, we first show that $l[\mathcal{I}] = MC.lunit\ MC.unity$ and $r[\mathcal{I}] = MC.runit\ MC.unity$, from which it follows by facts already proved for MC that both are equal to ι . We then show that for an arbitrary identity a the arrows $l[a]$ and $r[a]$ satisfy the equations that uniquely characterize the components $MC.lunit\ a$ and $MC.runit\ a$, respectively, and are therefore equal to those components.

lemma *unitor-coincidence*:

shows $l[\mathcal{I}] = \iota$ **and** $r[\mathcal{I}] = \iota$

proof –

have $r[\mathcal{I}] = MC.runit\ MC.unity$

by (*metis* (*no-types*, *lifting*) $MC.arr$ -runit $MC.runit$ -eqI $MC.unitor$ -coincidence(2) T -simp \mathcal{I} -agreement ι -def α -ide-simp ideD(1) ide-unity iso-is-arr iso-runit runit-in-hom triangle)

moreover have $l[\mathcal{I}] = MC.lunit\ MC.unity$

using $MC.unitor$ -coincidence(1) ι -def **by** *force*

ultimately have 1: $l[\mathcal{I}] = \iota \wedge r[\mathcal{I}] = \iota$

using $MC.unitor$ -coincidence **by** *simp*

show $l[\mathcal{I}] = \iota$ **using** 1 **by** *simp*

show $r[\mathcal{I}] = \iota$ **using** 1 **by** *simp*

qed

lemma *lunit-char*:

assumes ide a

shows $\mathcal{I} \otimes l[a] = (\iota \otimes a) \cdot inv\ a[\mathcal{I}, \mathcal{I}, a]$

by (*metis* $MC.iso$ -assoc α -ide-simp ι -in-hom arrI arr-tensor *assms* ideD(1) ide-unity invert-side-of-triangle(2) triangle unitor-coincidence(2))

lemma *runit-char*:

assumes ide a

shows $r[a] \otimes \mathcal{I} = (a \otimes \iota) \cdot a[a, \mathcal{I}, \mathcal{I}]$

using *assms* triangle ι -def **by** *simp*

lemma *l-agreement*:

shows $MC.l = (\lambda f. \text{if } arr\ f \text{ then } f \cdot l[dom\ f] \text{ else null})$

proof
fix f
have $\neg \text{arr } f \implies MC.l f = \text{null}$ **by** *simp*
moreover have $\text{arr } f \implies MC.l f = f \cdot l[\text{dom } f]$
proof –
have $\bigwedge a. \text{ide } a \implies l[a] = MC.lunit a$
using *I-agreement T-def lunit-char ι-in-hom iso-lunit*
apply (*intro MC.lunit-eqI*)
apply *auto*
by *blast*
thus *?thesis*
by (*metis ide-dom ext seqE*)
qed
ultimately show $MC.l f = (\text{if } \text{arr } f \text{ then } f \cdot l[\text{dom } f] \text{ else null})$ **by** *simp*
qed

lemma *ρ-agreement*:
shows $MC.ρ = (\lambda f. \text{if } \text{arr } f \text{ then } f \cdot r[\text{dom } f] \text{ else null})$
proof
fix f
have $\neg \text{arr } f \implies MC.ρ f = \text{null}$ **by** *simp*
moreover have $\text{arr } f \implies MC.ρ f = f \cdot r[\text{dom } f]$
proof –
have $\bigwedge a. \text{ide } a \implies r[a] = MC.runit a$
using *I-agreement T-def runit-char ι-in-hom iso-runit*
apply (*intro MC.runit-eqI*)
apply *auto*
by *blast*
thus *?thesis*
by (*metis ide-dom local.ext seqE*)
qed
ultimately show $MC.ρ f = (\text{if } \text{arr } f \text{ then } f \cdot r[\text{dom } f] \text{ else null})$ **by** *simp*
qed

lemma *lunit-agreement*:
assumes *ide a*
shows $MC.lunit a = l[a]$
using *assms comp-cod-arr l-agreement*
by (*metis (no-types, lifting) MC.l-ide-simp ide-char in-homE lunit-in-hom*)

lemma *runit-agreement*:
assumes *ide a*
shows $MC.runit a = r[a]$
using *assms comp-cod-arr ρ-agreement*
by (*metis (no-types, lifting) MC.ρ-ide-simp ide-char in-homE runit-in-hom*)

end

2.3 Strict Monoidal Category

A monoidal category is *strict* if the components of the associator and unitors are all identities.

```

locale strict-monoidal-category =
  monoidal-category +
assumes strict-assoc:  $\llbracket \text{ide } a0; \text{ide } a1; \text{ide } a2 \rrbracket \implies \text{ide } a[a0, a1, a2]$ 
and strict-lunit:  $\text{ide } a \implies \text{l}[a] = a$ 
and strict-runit:  $\text{ide } a \implies \text{r}[a] = a$ 
begin

  lemma strict-unit:
shows  $\iota = \mathcal{I}$ 
  using strict-lunit unitor-coincidence(1) by auto

  lemma tensor-assoc [simp]:
assumes arr f0 and arr f1 and arr f2
shows  $(f0 \otimes f1) \otimes f2 = f0 \otimes f1 \otimes f2$ 
  by (metis CC.arrIPC CCC.arrIPC  $\alpha'$ .preserves-reflects-arr  $\alpha'$ -simp assms(1-3)
    assoc'-naturality ide-cod ide-dom inv-ide comp-arr-ide comp-ide-arr strict-assoc)

end

```

2.4 Opposite Monoidal Category

The *opposite* of a monoidal category has the same underlying category, but the arguments to the tensor product are reversed and the associator is inverted and its arguments reversed.

```

locale opposite-monoidal-category =
  C: monoidal-category C TC  $\alpha_C$   $\iota$ 
for C :: 'a comp (infixr  $\langle \cdot \rangle$  55)
and TC :: 'a * 'a  $\Rightarrow$  'a
and  $\alpha_C$  :: 'a * 'a * 'a  $\Rightarrow$  'a
and  $\iota$  :: 'a
begin

  abbreviation T
where  $T f \equiv T_C (\text{snd } f, \text{fst } f)$ 

  abbreviation  $\alpha$ 
where  $\alpha f \equiv C.\alpha' (\text{snd } (\text{snd } f), \text{fst } (\text{snd } f), \text{fst } f)$ 

end

sublocale opposite-monoidal-category  $\subseteq$  monoidal-category C T  $\alpha$   $\iota$ 
proof –
  interpret T: binary-endofunctor C T

```

```

    using C.T.extensionality C.CC.seq-char C.interchange by (unfold-locales, auto)
  interpret ToTC: functor C.CCC.comp C T.ToTC
    using T.functor-ToTC by auto
  interpret ToCT: functor C.CCC.comp C T.ToCT
    using T.functor-ToCT by auto
  interpret  $\alpha$ : natural-transformation C.CCC.comp C T.ToTC T.ToCT  $\alpha$ 
    using C. $\alpha'$ .extensionality C.CCC.dom-char C.CCC.cod-char T.ToTC-def T.ToCT-def
      C. $\alpha'$ .simp C. $\alpha'$ .naturality
    by (unfold-locales) auto
  interpret  $\alpha$ : natural-isomorphism C.CCC.comp C T.ToTC T.ToCT  $\alpha$ 
    using C. $\alpha'$ .components-are-iso by (unfold-locales, simp)
  interpret L: equivalence-functor C C  $\langle \lambda f. T (C.cod \iota, f) \rangle$ 
    using C.R.equivalence-functor-axioms by simp
  interpret R: equivalence-functor C C  $\langle \lambda f. T (f, C.cod \iota) \rangle$ 
    using C.L.equivalence-functor-axioms by simp
  show monoidal-category C T  $\alpha \iota$ 
    using C.unit-is-iso C.pentagon' C.comp-assoc
    by (unfold-locales) auto
qed

```

```

context opposite-monoidal-category
begin

```

```

lemma lunit-simp:
  assumes C.ide a
  shows lunit a = C.runit a
    using assms lunit-char C.iso-assoc by (intro C.runit-eqI, auto)

```

```

lemma runit-simp:
  assumes C.ide a
  shows runit a = C.lunit a
    using assms runit-char C.iso-assoc by (intro C.lunit-eqI, auto)

```

```

end

```

2.5 Dual Monoidal Category

The *dual* of a monoidal category is obtained by reversing the arrows of the underlying category. The tensor product remains the same, but the associators and unitors are inverted.

```

locale dual-monoidal-category =
  M: monoidal-category
begin

  sublocale dual-category C ..
  sublocale MM: product-category comp comp ..
  interpretation T: binary-functor comp comp comp T
    using M.T.extensionality M.interchange MM.comp-char

```

by *unfold-locales auto*
interpretation *T*: *binary-endofunctor comp ..*
interpretation *ToTC*: *functor T.CCC.comp comp T.ToTC*
 using *T.functor-ToTC by blast*
interpretation *ToCT*: *functor T.CCC.comp comp T.ToCT*
 using *T.functor-ToCT by blast*
interpretation α : *natural-transformation T.CCC.comp comp T.ToTC T.ToCT M. α'*
 using *M. α' .extensionality M. α' .naturality1 M. α' .naturality2*
 by *unfold-locales auto*
interpretation α : *natural-isomorphism T.CCC.comp comp T.ToTC T.ToCT M. α'*
 by *unfold-locales auto*
interpretation *L*: *equivalence-functor comp comp $\langle M.tensor (cod (M.inv \iota)) \rangle$*
proof –
interpret *L*: *dual-equivalence-functor C C $\langle M.tensor \mathcal{I} \rangle ..$*
show *equivalence-functor comp comp (M.tensor (cod (M.inv \iota)))*
 using *L.equivalence-functor-axioms*
 by *(simp add: M.unit-is-iso)*
qed
interpretation *R*: *equivalence-functor comp comp $\langle \lambda f. M.tensor f (cod (M.inv \iota)) \rangle$*
proof –
interpret *R*: *dual-equivalence-functor C C $\langle \lambda f. M.tensor f \mathcal{I} \rangle ..$*
show *equivalence-functor comp comp (M.tensor f (cod (M.inv \iota)))*
 using *R.equivalence-functor-axioms*
 by *(simp add: M.unit-is-iso)*
qed

sublocale *monoidal-category comp T M. α' $\langle M.inv \iota \rangle$*
 using *T.extensionality M.unit-in-hom M.inv-in-hom M.unit-is-iso M.pentagon'*
equivalence-functor-def category-axioms
 by *unfold-locales auto*

lemma *is-monoidal-category*:
shows *monoidal-category comp T M. α' (M.inv \iota)*
 ..

no-notation *comp (infixr $\langle \cdot \rangle$ 55)*

lemma *assoc-char*:
assumes *ide a and ide b and ide c*
shows *assoc a b c = M.assoc' a b c and assoc' a b c = M.assoc a b c*
 using *assms M.inv-inv M.iso-inv-iso*
apply *force*
by *(metis assms M. α' -ide-simp M.comp-assoc-assoc'(2) M.ideD(1) M.iso-assoc*
M.iso-cancel-left M.iso-inv-iso comp-assoc-assoc'(2) ide-char comp-def
tensor-preserves-ide)

lemma *lunit-char*:
assumes *ide a*
shows *lunit a = M.lunit' a*

```

proof –
  have  $M.lunit' a = lunit a$ 
  proof (intro lunit-eqI)
    show  $in-hom (M.lunit' a) (tensor\ unity\ a)\ a$ 
      using assms
      by (simp add: M.lunit'-in-hom M.unit-is-iso)
    show  $tensor\ unity (M.lunit' a) = comp (tensor (M.inv\ \iota)\ a) (assoc'\ unity\ unity\ a)$ 
  proof –
    have  $M.inv (tensor\ \mathcal{I} (M.lunit\ a) \cdot M.assoc\ \mathcal{I}\ \mathcal{I}\ a) = M.inv (tensor\ \iota\ a)$ 
      using assms M.triangle M.untor-coincidence by auto
    hence  $M.assoc'\ \mathcal{I}\ \mathcal{I}\ a \cdot tensor\ \mathcal{I} (M.lunit' a) = tensor (M.inv\ \iota)\ a$ 
      using assms M.inv-comp M.unit-is-iso by fastforce
    thus ?thesis
      using assms M.unit-is-iso assoc-char
         $M.invert-side-of-triangle(1)$ 
        [of tensor (M.inv \iota) a M.assoc' unity unity a tensor \mathcal{I} 1^{-1}[a]]
      by auto
    qed
  qed
  thus ?thesis by simp
qed

```

```

lemma runit-char:
assumes ide a
shows  $runit\ a = M.runit' a$ 
proof –
  have  $M.runit' a = runit a$ 
  proof (intro runit-eqI)
    show  $in-hom (M.runit' a) (tensor\ a\ unity)\ a$ 
      using assms
      by (simp add: M.runit'-in-hom M.unit-is-iso)
    show  $tensor (M.runit' a)\ unity = comp (tensor\ a\ (M.inv\ \iota)) (assoc\ a\ unity\ unity)$ 
  proof –
    have  $M.inv (tensor\ a\ \iota \cdot M.assoc\ a\ \mathcal{I}\ \mathcal{I}) = M.inv (tensor (M.runit\ a)\ \mathcal{I})$ 
      using assms M.triangle [of a \mathcal{I}] M.untor-coincidence by auto
    hence  $M.assoc'\ a\ \mathcal{I}\ \mathcal{I} \cdot tensor\ a (M.inv\ \iota) = tensor (M.runit' a)\ \mathcal{I}$ 
      using assms M.inv-comp M.unit-in-hom M.unit-is-iso by auto
    thus ?thesis
      using assms M.unit-is-iso assoc-char by auto
    qed
  qed
  thus ?thesis by simp
qed

```

end

2.6 Monoidal Language

In this section we assume that a category C is given, and we define a formal syntax of terms constructed from arrows of C using function symbols that correspond to unity, composition, tensor, the associator and its formal inverse, and the left and right unitors and their formal inverses. We will use this syntax to state and prove the coherence theorem and then to construct the free monoidal category generated by C .

```

locale monoidal-language =
  C: category C
  for C :: 'a comp          (infixr <·> 55)
begin

```

```

datatype (discs-sels) 't term =
  Prim 't          (⟨⟨-⟩⟩)
| Unity           (⟨ $\mathcal{I}$ ⟩)
| Tensor 't term 't term (⟨ $\otimes$ ⟩ 53)
| Comp 't term 't term (⟨ $\cdot$ ⟩ 55)
| Lunit 't term (⟨ $\mathbf{l}[-]$ ⟩)
| Lunit' 't term (⟨ $\mathbf{l}^{-1}[-]$ ⟩)
| Runit 't term (⟨ $\mathbf{r}[-]$ ⟩)
| Runit' 't term (⟨ $\mathbf{r}^{-1}[-]$ ⟩)
| Assoc 't term 't term 't term (⟨ $\mathbf{a}[-, -, -]$ ⟩)
| Assoc' 't term 't term 't term (⟨ $\mathbf{a}^{-1}[-, -, -]$ ⟩)

```

```

lemma not-is-Tensor-Unity:
shows  $\neg$  is-Tensor Unity
  by simp

```

We define formal domain and codomain functions on terms.

```

primrec Dom :: 'a term  $\Rightarrow$  'a term
where Dom ⟨f⟩ = ⟨C.dom f⟩
| Dom  $\mathcal{I}$  =  $\mathcal{I}$ 
| Dom (t  $\otimes$  u) = (Dom t  $\otimes$  Dom u)
| Dom (t  $\cdot$  u) = Dom u
| Dom  $\mathbf{l}[t]$  = ( $\mathcal{I}$   $\otimes$  Dom t)
| Dom  $\mathbf{l}^{-1}[t]$  = Dom t
| Dom  $\mathbf{r}[t]$  = (Dom t  $\otimes$   $\mathcal{I}$ )
| Dom  $\mathbf{r}^{-1}[t]$  = Dom t
| Dom  $\mathbf{a}[t, u, v]$  = ((Dom t  $\otimes$  Dom u)  $\otimes$  Dom v)
| Dom  $\mathbf{a}^{-1}[t, u, v]$  = (Dom t  $\otimes$  (Dom u  $\otimes$  Dom v))

```

```

primrec Cod :: 'a term  $\Rightarrow$  'a term
where Cod ⟨f⟩ = ⟨C.cod f⟩
| Cod  $\mathcal{I}$  =  $\mathcal{I}$ 
| Cod (t  $\otimes$  u) = (Cod t  $\otimes$  Cod u)
| Cod (t  $\cdot$  u) = Cod t
| Cod  $\mathbf{l}[t]$  = Cod t
| Cod  $\mathbf{l}^{-1}[t]$  = ( $\mathcal{I}$   $\otimes$  Cod t)
| Cod  $\mathbf{r}[t]$  = Cod t

```


$$\begin{aligned}
& | \text{Cod } \mathbf{r}^{-1}[t] = (\text{Cod } t \otimes \mathcal{I}) \\
& | \text{Cod } \mathbf{a}[t, u, v] = (\text{Cod } t \otimes (\text{Cod } u \otimes \text{Cod } v)) \\
& | \text{Cod } \mathbf{a}^{-1}[t, u, v] = ((\text{Cod } t \otimes \text{Cod } u) \otimes \text{Cod } v)
\end{aligned}$$

A term is a “formal arrow” if it is constructed from arrows of C in such a way that composition is applied only to formally composable pairs of terms.

primrec $\text{Arr} :: 'a \text{ term} \Rightarrow \text{bool}$
where $\text{Arr } \langle f \rangle = C.\text{arr } f$
 $| \text{Arr } \mathcal{I} = \text{True}$
 $| \text{Arr } (t \otimes u) = (\text{Arr } t \wedge \text{Arr } u)$
 $| \text{Arr } (t \cdot u) = (\text{Arr } t \wedge \text{Arr } u \wedge \text{Dom } t = \text{Cod } u)$
 $| \text{Arr } \mathbf{l}[t] = \text{Arr } t$
 $| \text{Arr } \mathbf{l}^{-1}[t] = \text{Arr } t$
 $| \text{Arr } \mathbf{r}[t] = \text{Arr } t$
 $| \text{Arr } \mathbf{r}^{-1}[t] = \text{Arr } t$
 $| \text{Arr } \mathbf{a}[t, u, v] = (\text{Arr } t \wedge \text{Arr } u \wedge \text{Arr } v)$
 $| \text{Arr } \mathbf{a}^{-1}[t, u, v] = (\text{Arr } t \wedge \text{Arr } u \wedge \text{Arr } v)$

abbreviation $\text{Par} :: 'a \text{ term} \Rightarrow 'a \text{ term} \Rightarrow \text{bool}$
where $\text{Par } t \ u \equiv \text{Arr } t \wedge \text{Arr } u \wedge \text{Dom } t = \text{Dom } u \wedge \text{Cod } t = \text{Cod } u$

abbreviation $\text{Seq} :: 'a \text{ term} \Rightarrow 'a \text{ term} \Rightarrow \text{bool}$
where $\text{Seq } t \ u \equiv \text{Arr } t \wedge \text{Arr } u \wedge \text{Dom } t = \text{Cod } u$

abbreviation $\text{Hom} :: 'a \text{ term} \Rightarrow 'a \text{ term} \Rightarrow 'a \text{ term set}$
where $\text{Hom } a \ b \equiv \{ t. \text{Arr } t \wedge \text{Dom } t = a \wedge \text{Cod } t = b \}$

A term is a “formal identity” if it is constructed from identity arrows of C and \mathcal{I} using only the \otimes operator.

primrec $\text{Ide} :: 'a \text{ term} \Rightarrow \text{bool}$
where $\text{Ide } \langle f \rangle = C.\text{ide } f$
 $| \text{Ide } \mathcal{I} = \text{True}$
 $| \text{Ide } (t \otimes u) = (\text{Ide } t \wedge \text{Ide } u)$
 $| \text{Ide } (t \cdot u) = \text{False}$
 $| \text{Ide } \mathbf{l}[t] = \text{False}$
 $| \text{Ide } \mathbf{l}^{-1}[t] = \text{False}$
 $| \text{Ide } \mathbf{r}[t] = \text{False}$
 $| \text{Ide } \mathbf{r}^{-1}[t] = \text{False}$
 $| \text{Ide } \mathbf{a}[t, u, v] = \text{False}$
 $| \text{Ide } \mathbf{a}^{-1}[t, u, v] = \text{False}$

lemma Ide-implies-Arr [*simp*]:
shows $\text{Ide } t \Longrightarrow \text{Arr } t$
by (*induct t*) *auto*

lemma $\text{Arr-implies-Ide-Dom}$:
shows $\text{Arr } t \Longrightarrow \text{Ide } (\text{Dom } t)$
by (*induct t*) *auto*

lemma *Arr-implies-Ide-Cod*:
shows $Arr\ t \implies Ide\ (Cod\ t)$
by *(induct t) auto*

lemma *Ide-in-Hom [simp]*:
shows $Ide\ t \implies t \in Hom\ t\ t$
by *(induct t) auto*

A formal arrow is “canonical” if the only arrows of C used in its construction are identities.

primrec $Can :: 'a\ term \Rightarrow bool$
where $Can\ \langle f \rangle = C.ide\ f$
| $Can\ \mathcal{I} = True$
| $Can\ (t \otimes u) = (Can\ t \wedge Can\ u)$
| $Can\ (t \cdot u) = (Can\ t \wedge Can\ u \wedge Dom\ t = Cod\ u)$
| $Can\ \mathbf{l}[t] = Can\ t$
| $Can\ \mathbf{l}^{-1}[t] = Can\ t$
| $Can\ \mathbf{r}[t] = Can\ t$
| $Can\ \mathbf{r}^{-1}[t] = Can\ t$
| $Can\ \mathbf{a}[t, u, v] = (Can\ t \wedge Can\ u \wedge Can\ v)$
| $Can\ \mathbf{a}^{-1}[t, u, v] = (Can\ t \wedge Can\ u \wedge Can\ v)$

lemma *Ide-implies-Can*:
shows $Ide\ t \implies Can\ t$
by *(induct t) auto*

lemma *Can-implies-Arr*:
shows $Can\ t \implies Arr\ t$
by *(induct t) auto*

We next define the formal inverse of a term. This is only sensible for formal arrows built using only isomorphisms of C ; in particular, for canonical formal arrows.

primrec $Inv :: 'a\ term \Rightarrow 'a\ term$
where $Inv\ \langle f \rangle = \langle C.inv\ f \rangle$
| $Inv\ \mathcal{I} = \mathcal{I}$
| $Inv\ (t \otimes u) = (Inv\ t \otimes Inv\ u)$
| $Inv\ (t \cdot u) = (Inv\ u \cdot Inv\ t)$
| $Inv\ \mathbf{l}[t] = \mathbf{l}^{-1}[Inv\ t]$
| $Inv\ \mathbf{l}^{-1}[t] = \mathbf{l}[Inv\ t]$
| $Inv\ \mathbf{r}[t] = \mathbf{r}^{-1}[Inv\ t]$
| $Inv\ \mathbf{r}^{-1}[t] = \mathbf{r}[Inv\ t]$
| $Inv\ \mathbf{a}[t, u, v] = \mathbf{a}^{-1}[Inv\ t, Inv\ u, Inv\ v]$
| $Inv\ \mathbf{a}^{-1}[t, u, v] = \mathbf{a}[Inv\ t, Inv\ u, Inv\ v]$

lemma *Inv-preserves-Ide*:
shows $Ide\ t \implies Ide\ (Inv\ t)$
by *(induct t) auto*

lemma *Inv-preserves-Can*:

```

assumes  $Can\ t$ 
shows  $Can\ (Inv\ t)$  and  $Dom\ (Inv\ t) = Cod\ t$  and  $Cod\ (Inv\ t) = Dom\ t$ 
proof –
  have  $0: Can\ t \implies Can\ (Inv\ t) \wedge Dom\ (Inv\ t) = Cod\ t \wedge Cod\ (Inv\ t) = Dom\ t$ 
    by  $(induct\ t)\ auto$ 
  show  $Can\ (Inv\ t)$  using  $assms\ 0$  by  $blast$ 
  show  $Dom\ (Inv\ t) = Cod\ t$  using  $assms\ 0$  by  $blast$ 
  show  $Cod\ (Inv\ t) = Dom\ t$  using  $assms\ 0$  by  $blast$ 
qed

```

```

lemma  $Inv\text{-in-Hom}$  [ $simp$ ]:
assumes  $Can\ t$ 
shows  $Inv\ t \in Hom\ (Cod\ t)\ (Dom\ t)$ 
  using  $assms\ Inv\text{-preserves-Can}\ Can\text{-implies-Arr}$  by  $simp$ 

```

```

lemma  $Inv\text{-Ide}$  [ $simp$ ]:
assumes  $Ide\ a$ 
shows  $Inv\ a = a$ 
  using  $assms$  by  $(induct\ a)\ auto$ 

```

```

lemma  $Inv\text{-Inv}$  [ $simp$ ]:
assumes  $Can\ t$ 
shows  $Inv\ (Inv\ t) = t$ 
  using  $assms$  by  $(induct\ t)\ auto$ 

```

We call a term “diagonal” if it is either \mathcal{I} or it is constructed from arrows of C using only the \otimes operator associated to the right. Essentially, such terms are lists of arrows of C , where \mathcal{I} represents the empty list and \otimes is used as the list constructor. We call them “diagonal” because terms can be regarded as defining “interconnection matrices” of arrows connecting “inputs” to “outputs”, and from this point of view diagonal terms correspond to diagonal matrices. The matrix point of view is suggestive for the extension of the results presented here to the symmetric monoidal and cartesian monoidal cases.

```

fun  $Diag :: 'a\ term \Rightarrow bool$ 
where  $Diag\ \mathcal{I} = True$ 
  |  $Diag\ \langle f \rangle = C.arr\ f$ 
  |  $Diag\ (\langle f \rangle \otimes u) = (C.arr\ f \wedge Diag\ u \wedge u \neq \mathcal{I})$ 
  |  $Diag\ - = False$ 

```

```

lemma  $Diag\text{-TensorE}$ :
assumes  $Diag\ (Tensor\ t\ u)$ 
shows  $\langle un\text{-Prim}\ t \rangle = t$  and  $C.arr\ (un\text{-Prim}\ t)$  and  $Diag\ t$  and  $Diag\ u$  and  $u \neq \mathcal{I}$ 
proof –
  have  $1: t = \langle un\text{-Prim}\ t \rangle \wedge C.arr\ (un\text{-Prim}\ t) \wedge Diag\ t \wedge Diag\ u \wedge u \neq \mathcal{I}$ 
    using  $assms$  by  $(cases\ t; simp; cases\ u; simp)$ 
  show  $\langle un\text{-Prim}\ t \rangle = t$  using  $1$  by  $simp$ 
  show  $C.arr\ (un\text{-Prim}\ t)$  using  $1$  by  $simp$ 
  show  $Diag\ t$  using  $1$  by  $simp$ 
  show  $Diag\ u$  using  $1$  by  $simp$ 
  show  $u \neq \mathcal{I}$  using  $1$  by  $simp$ 

```

qed

lemma *Diag-implies-Arr*:

shows $Diag\ t \implies Arr\ t$

apply (*induct t, simp-all*)

by (*simp add: Diag-TensorE*)

lemma *Dom-preserves-Diag*:

shows $Diag\ t \implies Diag\ (Dom\ t)$

apply (*induct t, simp-all*)

proof –

fix $u\ v$

assume $I2: Diag\ v \implies Diag\ (Dom\ v)$

assume $uv: Diag\ (u \otimes v)$

show $Diag\ (Dom\ u \otimes Dom\ v)$

proof –

have $1: is-Prim\ (Dom\ u) \wedge C.arr\ (un-Prim\ (Dom\ u)) \wedge$
 $Dom\ u = \langle C.dom\ (un-Prim\ u) \rangle$

using uv **by** (*cases u; simp; cases v, simp-all*)

have $2: Diag\ v \wedge v \neq \mathcal{I} \wedge \neg is-Comp\ v \wedge \neg is-Lunit'\ v \wedge \neg is-Runit'\ v$

using uv **by** (*cases u; simp; cases v, simp-all*)

have $Diag\ (Dom\ v) \wedge Dom\ v \neq \mathcal{I}$

using $2\ I2$ **by** (*cases v, simp-all*)

thus *?thesis* **using** 1 **by** *force*

qed

qed

lemma *Cod-preserves-Diag*:

shows $Diag\ t \implies Diag\ (Cod\ t)$

apply (*induct t, simp-all*)

proof –

fix $u\ v$

assume $I2: Diag\ v \implies Diag\ (Cod\ v)$

assume $uv: Diag\ (u \otimes v)$

show $Diag\ (Cod\ u \otimes Cod\ v)$

proof –

have $1: is-Prim\ (Cod\ u) \wedge C.arr\ (un-Prim\ (Cod\ u)) \wedge Cod\ u = \langle C.cod\ (un-Prim\ u) \rangle$
using uv **by** (*cases u; simp; cases v; simp*)

have $2: Diag\ v \wedge v \neq \mathcal{I} \wedge \neg is-Comp\ v \wedge \neg is-Lunit'\ v \wedge \neg is-Runit'\ v$

using uv **by** (*cases u; simp; cases v; simp*)

have $Diag\ (Cod\ v) \wedge Cod\ v \neq \mathcal{I}$

using $I2\ 2$ **by** (*cases v, simp-all*)

thus *?thesis* **using** 1 **by** *force*

qed

qed

lemma *Inv-preserves-Diag*:

assumes *Can t* **and** *Diag t*

shows $Diag\ (Inv\ t)$

proof –
have $Can\ t \wedge Diag\ t \implies Diag\ (Inv\ t)$
apply (*induct t, simp-all*)
by (*metis (no-types, lifting) Can.simps(1) Inv.simps(1) Inv.simps(2) Diag.simps(3)*
Inv-Inv Diag-TensorE(1) C.inv-ide)
thus *?thesis* **using** *assms* **by** *blast*
qed

The following function defines the “dimension” of a term, which is the number of arrows of (\cdot) it contains. For diagonal terms, this is just the length of the term when regarded as a list of arrows of (\cdot) . Alternatively, if a term is regarded as defining an interconnection matrix, then the dimension is the number of inputs (or outputs).

primrec $dim :: 'a\ term \Rightarrow nat$
where $dim\ \langle f \rangle = 1$
 $| dim\ \mathcal{I} = 0$
 $| dim\ (t \otimes u) = (dim\ t + dim\ u)$
 $| dim\ (t \cdot u) = dim\ t$
 $| dim\ \mathbf{l}[t] = dim\ t$
 $| dim\ \mathbf{l}^{-1}[t] = dim\ t$
 $| dim\ \mathbf{r}[t] = dim\ t$
 $| dim\ \mathbf{r}^{-1}[t] = dim\ t$
 $| dim\ \mathbf{a}[t, u, v] = dim\ t + dim\ u + dim\ v$
 $| dim\ \mathbf{a}^{-1}[t, u, v] = dim\ t + dim\ u + dim\ v$

The following function defines a tensor product for diagonal terms. If terms are regarded as lists, this is just list concatenation. If terms are regarded as matrices, this corresponds to constructing a block diagonal matrix.

fun $TensorDiag$ (**infixr** $\langle [\otimes] \rangle$ 53)
where $\mathcal{I}\ [\otimes]\ u = u$
 $| t\ [\otimes]\ \mathcal{I} = t$
 $| \langle f \rangle\ [\otimes]\ u = \langle f \rangle \otimes u$
 $| (t \otimes u)\ [\otimes]\ v = t\ [\otimes]\ (u\ [\otimes]\ v)$
 $| t\ [\otimes]\ u = undefined$

lemma $TensorDiag-Prim$ [*simp*]:
assumes $t \neq \mathcal{I}$
shows $\langle f \rangle\ [\otimes]\ t = \langle f \rangle \otimes t$
using *assms* **by** (*cases t, simp-all*)

lemma $TensorDiag-term-Unity$ [*simp*]:
shows $t\ [\otimes]\ \mathcal{I} = t$
by (*cases t = \mathcal{I}; cases t, simp-all*)

lemma $TensorDiag-Diag$:
assumes $Diag\ (t \otimes u)$
shows $t\ [\otimes]\ u = t \otimes u$
using *assms TensorDiag-Prim* **by** (*cases t, simp-all*)

lemma $TensorDiag-preserves-Diag$:

assumes $Diag\ t$ and $Diag\ u$
shows $Diag\ (t \lfloor \otimes \rfloor u)$
and $Dom\ (t \lfloor \otimes \rfloor u) = Dom\ t \lfloor \otimes \rfloor Dom\ u$
and $Cod\ (t \lfloor \otimes \rfloor u) = Cod\ t \lfloor \otimes \rfloor Cod\ u$
proof –
have $0: \bigwedge u. \llbracket Diag\ t; Diag\ u \rrbracket \implies$
 $Diag\ (t \lfloor \otimes \rfloor u) \wedge Dom\ (t \lfloor \otimes \rfloor u) = Dom\ t \lfloor \otimes \rfloor Dom\ u \wedge$
 $Cod\ (t \lfloor \otimes \rfloor u) = Cod\ t \lfloor \otimes \rfloor Cod\ u$
apply (*induct t, simp-all*)
proof –
fix $f :: 'a$ and $u :: 'a\ term$
assume $f: C.arr\ f$
assume $u: Diag\ u$
show $Diag\ (\langle f \rangle \lfloor \otimes \rfloor u) \wedge Dom\ (\langle f \rangle \lfloor \otimes \rfloor u) = \langle C.dom\ f \rangle \lfloor \otimes \rfloor Dom\ u \wedge$
 $Cod\ (\langle f \rangle \lfloor \otimes \rfloor u) = \langle C.cod\ f \rangle \lfloor \otimes \rfloor Cod\ u$
using $u\ f$ by (*cases u, simp-all*)
next
fix $u\ v\ w$
assume $I1: \bigwedge u. Diag\ v \implies Diag\ u \implies Diag\ (v \lfloor \otimes \rfloor u) \wedge$
 $Dom\ (v \lfloor \otimes \rfloor u) = Dom\ v \lfloor \otimes \rfloor Dom\ u \wedge$
 $Cod\ (v \lfloor \otimes \rfloor u) = Cod\ v \lfloor \otimes \rfloor Cod\ u$
assume $I2: \bigwedge u. Diag\ w \implies Diag\ u \implies Diag\ (w \lfloor \otimes \rfloor u) \wedge$
 $Dom\ (w \lfloor \otimes \rfloor u) = Dom\ w \lfloor \otimes \rfloor Dom\ u \wedge$
 $Cod\ (w \lfloor \otimes \rfloor u) = Cod\ w \lfloor \otimes \rfloor Cod\ u$
assume $vw: Diag\ (v \otimes w)$
assume $u: Diag\ u$
show $Diag\ ((v \otimes w) \lfloor \otimes \rfloor u) \wedge$
 $Dom\ ((v \otimes w) \lfloor \otimes \rfloor u) = (Dom\ v \otimes Dom\ w) \lfloor \otimes \rfloor Dom\ u \wedge$
 $Cod\ ((v \otimes w) \lfloor \otimes \rfloor u) = (Cod\ v \otimes Cod\ w) \lfloor \otimes \rfloor Cod\ u$
proof –
have $v: v = \langle un-Prim\ v \rangle \wedge Diag\ v$
using $vw\ Diag-implies-Arr\ Diag-TensorE$ [of $v\ w$] by *force*
have $w: Diag\ w$
using vw by (*simp add: Diag-TensorE*)
have $u = \mathcal{I} \implies ?thesis$ by (*simp add: vw*)
moreover **have** $u \neq \mathcal{I} \implies ?thesis$
using $u\ v\ w\ I1\ I2\ Dom-preserves-Diag$ [of u] $Cod-preserves-Diag$ [of u]
by (*cases u, simp-all*)
ultimately show $?thesis$ by *blast*
qed
qed
show $Diag\ (t \lfloor \otimes \rfloor u)$ **using** *assms 0* by *blast*
show $Dom\ (t \lfloor \otimes \rfloor u) = Dom\ t \lfloor \otimes \rfloor Dom\ u$ **using** *assms 0* by *blast*
show $Cod\ (t \lfloor \otimes \rfloor u) = Cod\ t \lfloor \otimes \rfloor Cod\ u$ **using** *assms 0* by *blast*
qed

lemma *TensorDiag-in-Hom*:

assumes $Diag\ t$ and $Diag\ u$

shows $t \lfloor \otimes \rfloor u \in Hom\ (Dom\ t \lfloor \otimes \rfloor Dom\ u)\ (Cod\ t \lfloor \otimes \rfloor Cod\ u)$

using *assms TensorDiag-preserves-Diag Diag-implies-Arr* **by** *simp*

lemma *Dom-TensorDiag*:

assumes *Diag t* **and** *Diag u*

shows $\text{Dom } (t \llbracket \otimes \rrbracket u) = \text{Dom } t \llbracket \otimes \rrbracket \text{Dom } u$

using *assms TensorDiag-preserves-Diag(2)* **by** *simp*

lemma *Cod-TensorDiag*:

assumes *Diag t* **and** *Diag u*

shows $\text{Cod } (t \llbracket \otimes \rrbracket u) = \text{Cod } t \llbracket \otimes \rrbracket \text{Cod } u$

using *assms TensorDiag-preserves-Diag(3)* **by** *simp*

lemma *not-is-Tensor-TensorDiagE*:

assumes $\neg \text{is-Tensor } (t \llbracket \otimes \rrbracket u)$ **and** *Diag t* **and** *Diag u*

and $t \neq \mathcal{I}$ **and** $u \neq \mathcal{I}$

shows *False*

proof –

have $\llbracket \neg \text{is-Tensor } (t \llbracket \otimes \rrbracket u); \text{Diag } t; \text{Diag } u; t \neq \mathcal{I}; u \neq \mathcal{I} \rrbracket \implies \text{False}$

apply (*induct t, simp-all*)

proof –

fix $v w$

assume $I2: \neg \text{is-Tensor } (w \llbracket \otimes \rrbracket u) \implies \text{Diag } w \implies w \neq \mathcal{I} \implies \text{False}$

assume $1: \neg \text{is-Tensor } ((v \otimes w) \llbracket \otimes \rrbracket u)$

assume $vw: \text{Diag } (v \otimes w)$

assume $u: \text{Diag } u$

assume $2: u \neq \mathcal{I}$

show *False*

proof –

have $v: v = \langle \text{un-Prim } v \rangle$

using vw *Diag-TensorE* [*of v w*] **by** *force*

have $w: \text{Diag } w \wedge w \neq \mathcal{I}$

using vw *Diag-TensorE* [*of v w*] **by** *simp*

have $(v \otimes w) \llbracket \otimes \rrbracket u = v \otimes (w \llbracket \otimes \rrbracket u)$

proof –

have $(v \otimes w) \llbracket \otimes \rrbracket u = v \llbracket \otimes \rrbracket (w \llbracket \otimes \rrbracket u)$

using u 2 **by** (*cases u, simp-all*)

also have $\dots = v \otimes (w \llbracket \otimes \rrbracket u)$

using u v $I2$ *TensorDiag-Prim not-is-Tensor-Unity* **by** *metis*

finally show *?thesis* **by** *simp*

qed

thus *?thesis* **using** 1 **by** *simp*

qed

qed

thus *?thesis* **using** *assms* **by** *blast*

qed

lemma *TensorDiag-assoc*:

assumes *Diag t* **and** *Diag u* **and** *Diag v*

shows $(t \llbracket \otimes \rrbracket u) \llbracket \otimes \rrbracket v = t \llbracket \otimes \rrbracket (u \llbracket \otimes \rrbracket v)$

proof –
have $\bigwedge n t u v. \llbracket \dim t = n; \text{Diag } t; \text{Diag } u; \text{Diag } v \rrbracket \implies$
 $(t \llbracket \otimes \rrbracket u) \llbracket \otimes \rrbracket v = t \llbracket \otimes \rrbracket (u \llbracket \otimes \rrbracket v)$

proof –
fix n
show $\bigwedge t u v. \llbracket \dim t = n; \text{Diag } t; \text{Diag } u; \text{Diag } v \rrbracket \implies$
 $(t \llbracket \otimes \rrbracket u) \llbracket \otimes \rrbracket v = t \llbracket \otimes \rrbracket (u \llbracket \otimes \rrbracket v)$

proof (*induction n rule: nat-less-induct*)
fix $n :: \text{nat}$ **and** $t :: 'a \text{ term}$ **and** $u v$
assume $I: \forall m < n. \forall t u v. \dim t = m \longrightarrow \text{Diag } t \longrightarrow \text{Diag } u \longrightarrow \text{Diag } v \longrightarrow$
 $(t \llbracket \otimes \rrbracket u) \llbracket \otimes \rrbracket v = t \llbracket \otimes \rrbracket (u \llbracket \otimes \rrbracket v)$

assume $\dim: \dim t = n$
assume $t: \text{Diag } t$
assume $u: \text{Diag } u$
assume $v: \text{Diag } v$
show $(t \llbracket \otimes \rrbracket u) \llbracket \otimes \rrbracket v = t \llbracket \otimes \rrbracket (u \llbracket \otimes \rrbracket v)$

proof –
have $t = \mathcal{I} \implies ?thesis$ **by** *simp*
moreover **have** $u = \mathcal{I} \implies ?thesis$ **by** *simp*
moreover **have** $v = \mathcal{I} \implies ?thesis$ **by** *simp*
moreover **have** $t \neq \mathcal{I} \wedge u \neq \mathcal{I} \wedge v \neq \mathcal{I} \wedge \text{is-Prim } t \implies ?thesis$
using v **by** (*cases t, simp-all, cases u, simp-all; cases v, simp-all*)
moreover **have** $t \neq \mathcal{I} \wedge u \neq \mathcal{I} \wedge v \neq \mathcal{I} \wedge \text{is-Tensor } t \implies ?thesis$
proof (*cases t; simp*)
fix $w :: 'a \text{ term}$ **and** $x :: 'a \text{ term}$
assume $1: u \neq \mathcal{I} \wedge v \neq \mathcal{I}$
assume $2: t = (w \otimes x)$
show $((w \otimes x) \llbracket \otimes \rrbracket u) \llbracket \otimes \rrbracket v = (w \otimes x) \llbracket \otimes \rrbracket (u \llbracket \otimes \rrbracket v)$

proof –
have $w: w = \langle \text{un-Prim } w \rangle$
using t 1 2 *Diag-TensorE* [*of w x*] **by** *auto*
have $x: \text{Diag } x$
using t w 1 2 **by** (*cases w, simp-all*)
have $((w \otimes x) \llbracket \otimes \rrbracket u) \llbracket \otimes \rrbracket v = (w \llbracket \otimes \rrbracket (x \llbracket \otimes \rrbracket u)) \llbracket \otimes \rrbracket v$
using u v w x 1 2 **by** (*cases u, simp-all*)
also **have** $\dots = (w \otimes (x \llbracket \otimes \rrbracket u)) \llbracket \otimes \rrbracket v$
using t w u 1 2 *TensorDiag-Prim not-is-Tensor-TensorDiagE Diag-TensorE*
not-is-Tensor-Unity
by *metis*
also **have** $\dots = w \llbracket \otimes \rrbracket ((x \llbracket \otimes \rrbracket u) \llbracket \otimes \rrbracket v)$
using u v w x 1 **by** (*cases u, simp-all; cases v, simp-all*)
also **have** $\dots = w \llbracket \otimes \rrbracket (x \llbracket \otimes \rrbracket (u \llbracket \otimes \rrbracket v))$

proof –
have $\dim x < \dim t$
using w 2 **by** (*cases w, simp-all*)
thus *?thesis*
using u v x $\dim I$ **by** *simp*

qed
also **have** $\dots = (w \otimes x) \llbracket \otimes \rrbracket (u \llbracket \otimes \rrbracket v)$

proof –
have \exists : *is-Tensor* ($u \llbracket \otimes \rrbracket v$)
using $u \ v \ 1$ *not-is-Tensor-TensorDiagE* **by** *auto*
obtain $u' :: 'a \text{ term and } v'$ **where** uv' : $u \llbracket \otimes \rrbracket v = u' \otimes v'$
using \exists *is-Tensor-def* **by** *blast*
thus *?thesis* **by** *simp*
qed
finally show *?thesis* **by** *simp*
qed
moreover have $t = \mathcal{I} \vee \text{is-Prim } t \vee \text{is-Tensor } t$
using t **by** (*cases t, simp-all*)
ultimately show *?thesis* **by** *blast*
qed
qed
qed
thus *?thesis* **using** *assms* **by** *blast*
qed

lemma *TensorDiag-preserves-Ide*:
assumes *Ide t and Ide u and Diag t and Diag u*
shows *Ide (t \llbracket \otimes \rrbracket u)*
using *assms*
by (*metis (mono-tags, lifting) Arr-implies-Ide-Dom Ide-in-Hom Diag-implies-Arr*
TensorDiag-preserves-Diag(1) TensorDiag-preserves-Diag(2) mem-Collect-eq)

lemma *TensorDiag-preserves-Can*:
assumes *Can t and Can u and Diag t and Diag u*
shows *Can (t \llbracket \otimes \rrbracket u)*
proof –
have $\bigwedge u. \llbracket \text{Can } t \wedge \text{Diag } t; \text{Can } u \wedge \text{Diag } u \rrbracket \implies \text{Can } (t \llbracket \otimes \rrbracket u)$
proof (*induct t; simp*)
show $\bigwedge x u. C.\text{ide } x \wedge C.\text{arr } x \implies \text{Can } u \wedge \text{Diag } u \implies \text{Can } (\langle x \rangle \llbracket \otimes \rrbracket u)$
by (*metis Ide.simps(1) Ide.simps(2) Ide-implies-Can Diag.simps(2) TensorDiag-Prim*
TensorDiag-preserves-Ide Can.simps(3))
show $\bigwedge t1 \ t2 \ u. (\bigwedge u. \text{Diag } t1 \implies \text{Can } u \wedge \text{Diag } u \implies \text{Can } (t1 \llbracket \otimes \rrbracket u)) \implies$
 $(\bigwedge u. \text{Diag } t2 \implies \text{Can } u \wedge \text{Diag } u \implies \text{Can } (t2 \llbracket \otimes \rrbracket u)) \implies$
 $\text{Can } t1 \wedge \text{Can } t2 \wedge \text{Diag } (t1 \otimes t2) \implies \text{Can } u \wedge \text{Diag } u \implies$
 $\text{Can } ((t1 \otimes t2) \llbracket \otimes \rrbracket u)$
by (*metis Diag-TensorE(3) Diag-TensorE(4) TensorDiag-Diag TensorDiag-assoc*
TensorDiag-preserves-Diag(1))
qed
thus *?thesis* **using** *assms* **by** *blast*
qed

lemma *Inv-TensorDiag*:
assumes *Can t and Can u and Diag t and Diag u*
shows *Inv (t \llbracket \otimes \rrbracket u) = Inv t \llbracket \otimes \rrbracket Inv u*
proof –

```

have  $\bigwedge u. \llbracket \text{Can } t \wedge \text{Diag } t; \text{Can } u \wedge \text{Diag } u \rrbracket \implies \text{Inv } (t \llbracket \otimes \rrbracket u) = \text{Inv } t \llbracket \otimes \rrbracket \text{Inv } u$ 
proof (induct t, simp-all)
  fix f u
  assume f: C.ide f  $\wedge$  C.arr f
  assume u: Can u  $\wedge$  Diag u
  show Inv ( $\langle f \rangle \llbracket \otimes \rrbracket u$ ) =  $\langle f \rangle \llbracket \otimes \rrbracket \text{Inv } u$ 
    using f u by (cases u, simp-all)
  next
  fix t u v
  assume I1:  $\bigwedge v. \llbracket \text{Diag } t; \text{Can } v \wedge \text{Diag } v \rrbracket \implies \text{Inv } (t \llbracket \otimes \rrbracket v) = \text{Inv } t \llbracket \otimes \rrbracket \text{Inv } v$ 
  assume I2:  $\bigwedge v. \llbracket \text{Diag } u; \text{Can } v \wedge \text{Diag } v \rrbracket \implies \text{Inv } (u \llbracket \otimes \rrbracket v) = \text{Inv } u \llbracket \otimes \rrbracket \text{Inv } v$ 
  assume tu: Can t  $\wedge$  Can u  $\wedge$  Diag (t  $\otimes$  u)
  have t: Can t  $\wedge$  Diag t
    using tu Diag-TensorE [of t u] by force
  have u: Can u  $\wedge$  Diag u
    using t tu by (cases t, simp-all)
  assume v: Can v  $\wedge$  Diag v
  show Inv ((t  $\otimes$  u)  $\llbracket \otimes \rrbracket v$ ) = (Inv t  $\otimes$  Inv u)  $\llbracket \otimes \rrbracket \text{Inv } v$ 
proof -
  have v = Unity  $\implies$  ?thesis by simp
  moreover have v  $\neq$  Unity  $\implies$  ?thesis
  proof -
    assume 1: v  $\neq$  Unity
    have Inv ((t  $\otimes$  u)  $\llbracket \otimes \rrbracket v$ ) = Inv (t  $\llbracket \otimes \rrbracket (u \llbracket \otimes \rrbracket v)$ )
      using 1 by (cases v, simp-all)
    also have ... = Inv t  $\llbracket \otimes \rrbracket \text{Inv } (u \llbracket \otimes \rrbracket v)$ 
      using t u v I1 TensorDiag-preserves-Diag TensorDiag-preserves-Can
        Inv-preserves-Diag Inv-preserves-Can
      by simp
    also have ... = Inv t  $\llbracket \otimes \rrbracket (\text{Inv } u \llbracket \otimes \rrbracket \text{Inv } v)$ 
      using t u v I2 TensorDiag-preserves-Diag TensorDiag-preserves-Can
        Inv-preserves-Diag Inv-preserves-Can
      by simp
    also have ... = (Inv t  $\otimes$  Inv u)  $\llbracket \otimes \rrbracket \text{Inv } v$ 
      using v 1 by (cases v, simp-all)
    finally show ?thesis by blast
  qed
  ultimately show ?thesis by blast
qed
qed
thus ?thesis using assms by blast
qed

```

The following function defines composition for compatible diagonal terms, by “pushing the composition down” to arrows of C .

```

fun CompDiag :: 'a term  $\Rightarrow$  'a term  $\Rightarrow$  'a term    (infixr  $\langle \cdot \rangle$  55)
where  $\mathcal{I} \llbracket \cdot \rrbracket u = u$ 
  |  $\langle f \rangle \llbracket \cdot \rrbracket \langle g \rangle = \langle f \cdot g \rangle$ 
  |  $(u \otimes v) \llbracket \cdot \rrbracket (w \otimes x) = (u \llbracket \cdot \rrbracket w \otimes v \llbracket \cdot \rrbracket x)$ 

```

| $t \llbracket \cdot \rrbracket \mathcal{I} = t$
| $t \llbracket \cdot \rrbracket - = \text{undefined} \cdot \text{undefined}$

Note that the last clause above is not relevant to diagonal terms. We have chosen a provably non-diagonal value in order to validate associativity.

lemma *CompDiag-preserves-Diag*:

assumes *Diag t and Diag u and Dom t = Cod u*

shows *Diag (t $\llbracket \cdot \rrbracket$ u)*

and *Dom (t $\llbracket \cdot \rrbracket$ u) = Dom u*

and *Cod (t $\llbracket \cdot \rrbracket$ u) = Cod t*

proof –

have 0 : $\bigwedge u. \llbracket \text{Diag } t; \text{Diag } u; \text{Dom } t = \text{Cod } u \rrbracket \implies$

$\text{Diag } (t \llbracket \cdot \rrbracket u) \wedge \text{Dom } (t \llbracket \cdot \rrbracket u) = \text{Dom } u \wedge \text{Cod } (t \llbracket \cdot \rrbracket u) = \text{Cod } t$

proof (*induct t, simp-all add: Diag-TensorE*)

fix $f u$

assume f : $C.\text{arr } f$

assume u : *Diag u*

assume 1 : $\langle C.\text{dom } f \rangle = \text{Cod } u$

show *Diag ($\langle f \rangle \llbracket \cdot \rrbracket u$) \wedge Dom ($\langle f \rangle \llbracket \cdot \rrbracket u$) = Dom u \wedge Cod ($\langle f \rangle \llbracket \cdot \rrbracket u$) = $\langle C.\text{cod } f \rangle$*

using $f u 1$ **by** (*cases u, simp-all*)

next

fix $u v w$

assume $I2$: $\bigwedge u. \llbracket \text{Diag } u; \text{Dom } w = \text{Cod } u \rrbracket \implies$

$\text{Diag } (w \llbracket \cdot \rrbracket u) \wedge \text{Dom } (w \llbracket \cdot \rrbracket u) = \text{Dom } u \wedge \text{Cod } (w \llbracket \cdot \rrbracket u) = \text{Cod } w$

assume vw : *Diag (v \otimes w)*

have v : *Diag v*

using vw *Diag-TensorE [of v w]* **by** *force*

have w : *Diag w*

using vw *Diag-TensorE [of v w]* **by** *force*

assume u : *Diag u*

assume 1 : $(\text{Dom } v \otimes \text{Dom } w) = \text{Cod } u$

show *Diag ((v \otimes w) $\llbracket \cdot \rrbracket$ u) \wedge Dom ((v \otimes w) $\llbracket \cdot \rrbracket$ u) = Dom u \wedge*

Cod ((v \otimes w) $\llbracket \cdot \rrbracket$ u) = Cod v \otimes Cod w

using $u v w 1$

proof (*cases u, simp-all*)

fix $x y$

assume 2 : $u = \text{Tensor } x y$

have 4 : *is-Prim x \wedge x = $\langle \text{un-Prim } x \rangle \wedge C.\text{arr } (\text{un-Prim } x) \wedge \text{Diag } y \wedge y \neq \mathcal{I}$*

using $u 2$ **by** (*cases x, cases y, simp-all*)

have 5 : *is-Prim v \wedge v = $\langle \text{un-Prim } v \rangle \wedge C.\text{arr } (\text{un-Prim } v) \wedge \text{Diag } w \wedge w \neq \mathcal{I}$*

using $v w vw$ **by** (*cases v, simp-all*)

have 6 : $C.\text{dom } (\text{un-Prim } v) = C.\text{cod } (\text{un-Prim } x) \wedge \text{Dom } w = \text{Cod } y$

using $1 2 4 5$ **apply** (*cases u, simp-all*)

by (*metis Cod.simps(1) Dom.simps(1) term.simps(1)*)

have $(v \otimes w) \llbracket \cdot \rrbracket u = \langle \text{un-Prim } v \cdot \text{un-Prim } x \rangle \otimes w \llbracket \cdot \rrbracket y$

using $2 4 5 6$ *CompDiag.simps(2) [of un-Prim v un-Prim x]* **by** *simp*

moreover **have** *Diag ($\langle \text{un-Prim } v \cdot \text{un-Prim } x \rangle \otimes w \llbracket \cdot \rrbracket y$)*

proof –

have *Diag (w $\llbracket \cdot \rrbracket$ y)*

```

using I2 4 5 6 by simp
thus ?thesis
using 4 5 6 Diag.simps(3) [of un-Prim v · un-Prim x (w [·] y)]
by (cases w; cases y) auto
qed
ultimately show Diag (v [·] x ⊗ w [·] y) ∧
  Dom (v [·] x) = Dom x ∧ Dom (w [·] y) = Dom y ∧
  Cod (v [·] x) = Cod v ∧ Cod (w [·] y) = Cod w
using 4 5 6 I2
by (metis (full-types) C.cod-comp C.dom-comp Cod.simps(1) CompDiag.simps(2)
  Dom.simps(1) C.seqI)
qed
qed
show Diag (t [·] u) using assms 0 by blast
show Dom (t [·] u) = Dom u using assms 0 by blast
show Cod (t [·] u) = Cod t using assms 0 by blast
qed

```

lemma *CompDiag-in-Hom*:
assumes *Diag t* **and** *Diag u* **and** *Dom t = Cod u*
shows *t [·] u ∈ Hom (Dom u) (Cod t)*
using *assms CompDiag-preserves-Diag Diag-implies-Arr* **by** simp

lemma *Dom-CompDiag*:
assumes *Diag t* **and** *Diag u* **and** *Dom t = Cod u*
shows *Dom (t [·] u) = Dom u*
using *assms CompDiag-preserves-Diag(2)* **by** simp

lemma *Cod-CompDiag*:
assumes *Diag t* **and** *Diag u* **and** *Dom t = Cod u*
shows *Cod (t [·] u) = Cod t*
using *assms CompDiag-preserves-Diag(3)* **by** simp

lemma *CompDiag-Cod-Diag [simp]*:
assumes *Diag t*
shows *Cod t [·] t = t*
proof –
have *Diag t ⇒ Cod t [·] t = t*
using *C.comp-cod-arr*
apply (*induct t, auto*)
by (*auto simp add: Diag-TensorE*)
thus ?thesis **using** *assms* **by** blast
qed

lemma *CompDiag-Diag-Dom [simp]*:
assumes *Diag t*
shows *t [·] Dom t = t*
proof –
have *Diag t ⇒ t [·] Dom t = t*

```

using C.comp-arr-dom
apply (induct t, auto)
by (auto simp add: Diag-TensorE)
thus ?thesis using assms by blast
qed

```

```

lemma CompDiag-Ide-Diag [simp]:
assumes Diag t and Ide a and Dom a = Cod t
shows  $a \llbracket \cdot \rrbracket t = t$ 
using assms Ide-in-Hom by simp

```

```

lemma CompDiag-Diag-Ide [simp]:
assumes Diag t and Ide a and Dom t = Cod a
shows  $t \llbracket \cdot \rrbracket a = t$ 
using assms Ide-in-Hom by auto

```

```

lemma CompDiag-assoc:
assumes Diag t and Diag u and Diag v
and  $Dom\ t = Cod\ u$  and  $Dom\ u = Cod\ v$ 
shows  $(t \llbracket \cdot \rrbracket u) \llbracket \cdot \rrbracket v = t \llbracket \cdot \rrbracket (u \llbracket \cdot \rrbracket v)$ 
proof –

```

```

  have  $\bigwedge u\ v. \llbracket Diag\ t; Diag\ u; Diag\ v; Dom\ t = Cod\ u; Dom\ u = Cod\ v \rrbracket \implies$ 
     $(t \llbracket \cdot \rrbracket u) \llbracket \cdot \rrbracket v = t \llbracket \cdot \rrbracket (u \llbracket \cdot \rrbracket v)$ 

```

```

proof (induct t, simp-all)

```

```

  fix  $f\ u\ v$ 

```

```

  assume  $f: C.arr\ f$ 

```

```

  assume  $u: Diag\ u$ 

```

```

  assume  $v: Diag\ v$ 

```

```

  assume  $1: \langle C.dom\ f \rangle = Cod\ u$ 

```

```

  assume  $2: Dom\ u = Cod\ v$ 

```

```

  show  $(\langle f \rangle \llbracket \cdot \rrbracket u) \llbracket \cdot \rrbracket v = \langle f \rangle \llbracket \cdot \rrbracket (u \llbracket \cdot \rrbracket v)$ 

```

```

    using C.comp-assoc by (cases u, simp-all; cases v, simp-all)

```

```

  next

```

```

  fix  $u\ v\ w\ x$ 

```

```

  assume  $I1: \bigwedge u\ v. \llbracket Diag\ w; Diag\ u; Diag\ v; Dom\ w = Cod\ u; Dom\ u = Cod\ v \rrbracket \implies$ 
     $(w \llbracket \cdot \rrbracket u) \llbracket \cdot \rrbracket v = w \llbracket \cdot \rrbracket (u \llbracket \cdot \rrbracket v)$ 

```

```

  assume  $I2: \bigwedge u\ v. \llbracket Diag\ x; Diag\ u; Diag\ v; Dom\ x = Cod\ u; Dom\ u = Cod\ v \rrbracket \implies$ 
     $(x \llbracket \cdot \rrbracket u) \llbracket \cdot \rrbracket v = x \llbracket \cdot \rrbracket (u \llbracket \cdot \rrbracket v)$ 

```

```

  assume  $wx: Diag\ (w \otimes x)$ 

```

```

  assume  $u: Diag\ u$ 

```

```

  assume  $v: Diag\ v$ 

```

```

  assume  $1: (Dom\ w \otimes Dom\ x) = Cod\ u$ 

```

```

  assume  $2: Dom\ u = Cod\ v$ 

```

```

  show  $((w \otimes x) \llbracket \cdot \rrbracket u) \llbracket \cdot \rrbracket v = (w \otimes x) \llbracket \cdot \rrbracket (u \llbracket \cdot \rrbracket v)$ 

```

```

  proof –

```

```

    have  $w: Diag\ w$ 

```

```

      using  $wx\ Diag-TensorE$  by blast

```

```

    have  $x: Diag\ x$ 

```

```

      using  $wx\ Diag-TensorE$  by blast

```

```

have is-Tensor u
  using u 1 by (cases u) simp-all
thus ?thesis
  using u v apply (cases u, simp-all, cases v, simp-all)
proof –
  fix u1 u2 v1 v2
  assume 3: u = (u1 ⊗ u2)
  assume 4: v = (v1 ⊗ v2)
  show (w [·] u1 [·] v1 = w [·] u1 [·] v1 ∧
    (x [·] u2 [·] v2 = x [·] u2 [·] v2)
  proof –
    have Diag u1 ∧ Diag u2
      using u 3 Diag-TensorE by blast
    moreover have Diag v1 ∧ Diag v2
      using v 4 Diag-TensorE by blast
    ultimately show ?thesis using w x I1 I2 1 2 3 4 by simp
  qed
qed
qed
qed
thus ?thesis using assms by blast
qed

```

```

lemma CompDiag-preserves-Ide:
assumes Ide t and Ide u and Diag t and Diag u and Dom t = Cod u
shows Ide (t [·] u)
proof –
  have  $\bigwedge u. \llbracket \text{Ide } t; \text{Ide } u; \text{Diag } t; \text{Diag } u; \text{Dom } t = \text{Cod } u \rrbracket \implies \text{Ide } (\text{CompDiag } t \ u)$ 
    by (induct t; simp)
  thus ?thesis using assms by blast
qed

```

```

lemma CompDiag-preserves-Can:
assumes Can t and Can u and Diag t and Diag u and Dom t = Cod u
shows Can (t [·] u)
proof –
  have  $\bigwedge u. \llbracket \text{Can } t \wedge \text{Diag } t; \text{Can } u \wedge \text{Diag } u; \text{Dom } t = \text{Cod } u \rrbracket \implies \text{Can } (t \ [·] \ u)$ 
  proof (induct t, simp-all)
    fix t u v
    assume I1:  $\bigwedge v. \llbracket \text{Diag } t; \text{Can } v \wedge \text{Diag } v; \text{Dom } t = \text{Cod } v \rrbracket \implies \text{Can } (t \ [·] \ v)$ 
    assume I2:  $\bigwedge v. \llbracket \text{Diag } u; \text{Can } v \wedge \text{Diag } v; \text{Dom } u = \text{Cod } v \rrbracket \implies \text{Can } (u \ [·] \ v)$ 
    assume tu: Can t ∧ Can u ∧ Diag (t ⊗ u)
    have t: Can t ∧ Diag t
      using tu Diag-TensorE by blast
    have u: Can u ∧ Diag u
      using tu Diag-TensorE by blast
    assume v: Can v ∧ Diag v
    assume 1: (Dom t ⊗ Dom u) = Cod v
    show Can ((t ⊗ u) [·] v)
  qed

```

```

proof –
  have 2:  $(\text{Dom } t \otimes \text{Dom } u) = \text{Cod } v$  using 1 by simp
  show ?thesis
    using v 2
  proof (cases v; simp)
    fix w x
    assume wx:  $v = (w \otimes x)$ 
    have  $\text{Can } w \wedge \text{Diag } w$  using v wx Diag-TensorE [of w x] by auto
    moreover have  $\text{Can } x \wedge \text{Diag } x$  using v wx Diag-TensorE [of w x] by auto
    moreover have  $\text{Dom } t = \text{Cod } w$  using 2 wx by simp
    moreover have wx:  $\text{Dom } u = \text{Cod } x$  using 2 wx by simp
    ultimately show  $\text{Can } (t \llbracket \cdot \rrbracket w) \wedge \text{Can } (u \llbracket \cdot \rrbracket x)$ 
      using t u I1 I2 by simp
  qed
qed
qed
thus ?thesis using assms by blast
qed

```

lemma *Inv-CompDiag*:

assumes $\text{Can } t$ **and** $\text{Can } u$ **and** $\text{Diag } t$ **and** $\text{Diag } u$ **and** $\text{Dom } t = \text{Cod } u$

shows $\text{Inv } (t \llbracket \cdot \rrbracket u) = \text{Inv } u \llbracket \cdot \rrbracket \text{Inv } t$

proof –

have $\bigwedge u. \llbracket \text{Can } t \wedge \text{Diag } t; \text{Can } u \wedge \text{Diag } u; \text{Dom } t = \text{Cod } u \rrbracket \implies$
 $\text{Inv } (t \llbracket \cdot \rrbracket u) = \text{Inv } u \llbracket \cdot \rrbracket \text{Inv } t$

proof (*induct t, simp-all*)

show $\bigwedge x u. \llbracket C.\text{ide } x \wedge C.\text{arr } x; \text{Can } u \wedge \text{Diag } u; \langle x \rangle = \text{Cod } u \rrbracket \implies$
 $\text{Inv } u = \text{Inv } u \llbracket \cdot \rrbracket \text{Inv } (\text{Cod } u)$

by (*metis CompDiag-Diag-Dom Inv-Ide Inv-preserves-Can(2) Inv-preserves-Diag*
Ide.simps(1))

show $\bigwedge u. \text{Can } u \wedge \text{Diag } u \implies \mathcal{I} = \text{Cod } u \implies \text{Inv } u = \text{Inv } u \llbracket \cdot \rrbracket \mathcal{I}$

by (*simp add: Inv-preserves-Can(2) Inv-preserves-Diag*)

fix t u v

assume tu: $\text{Can } t \wedge \text{Can } u \wedge \text{Diag } (t \otimes u)$

have t: $\text{Can } t \wedge \text{Diag } t$

using tu *Diag-TensorE* **by** blast

have u: $\text{Can } u \wedge \text{Diag } u$

using tu *Diag-TensorE* **by** blast

assume I1: $\bigwedge v. \llbracket \text{Diag } t; \text{Can } v \wedge \text{Diag } v; \text{Dom } t = \text{Cod } v \rrbracket \implies$
 $\text{Inv } (t \llbracket \cdot \rrbracket v) = \text{Inv } v \llbracket \cdot \rrbracket \text{Inv } t$

assume I2: $\bigwedge v. \llbracket \text{Diag } u; \text{Can } v \wedge \text{Diag } v; \text{Dom } u = \text{Cod } v \rrbracket \implies$
 $\text{Inv } (u \llbracket \cdot \rrbracket v) = \text{Inv } v \llbracket \cdot \rrbracket \text{Inv } u$

assume v: $\text{Can } v \wedge \text{Diag } v$

assume 1: $(\text{Dom } t \otimes \text{Dom } u) = \text{Cod } v$

show $\text{Inv } ((t \otimes u) \llbracket \cdot \rrbracket v) = \text{Inv } v \llbracket \cdot \rrbracket (\text{Inv } t \otimes \text{Inv } u)$

using v 1

proof (*cases v, simp-all*)

fix w x

assume wx: $v = (w \otimes x)$

have $Can\ w \wedge Diag\ w$ **using** $v\ wx\ Diag\ TensorE$ [of $w\ x$] **by** *auto*
moreover have $Can\ x \wedge Diag\ x$ **using** $v\ wx\ Diag\ TensorE$ [of $w\ x$] **by** *auto*
moreover have $Dom\ t = Cod\ w$ **using** $wx\ 1$ **by** *simp*
moreover have $Dom\ u = Cod\ x$ **using** $wx\ 1$ **by** *simp*
ultimately show $Inv\ (t\ [\cdot]\ w) = Inv\ w\ [\cdot]\ Inv\ t \wedge$
 $Inv\ (u\ [\cdot]\ x) = Inv\ x\ [\cdot]\ Inv\ u$
using $t\ u\ I1\ I2$ **by** *simp*
qed
qed
thus *?thesis* **using** *assms* **by** *blast*
qed

lemma *Can-and-Diag-implies-Ide*:
assumes $Can\ t$ **and** $Diag\ t$
shows $Ide\ t$
proof –
have $\llbracket Can\ t; Diag\ t \rrbracket \implies Ide\ t$
apply (*induct t, simp-all*)
by (*simp add: Diag-TensorE*)
thus *?thesis* **using** *assms* **by** *blast*
qed

lemma *CompDiag-Can-Inv* [*simp*]:
assumes $Can\ t$ **and** $Diag\ t$
shows $t\ [\cdot]\ Inv\ t = Cod\ t$
using *assms Can-and-Diag-implies-Ide Ide-in-Hom* **by** *simp*

lemma *CompDiag-Inv-Can* [*simp*]:
assumes $Can\ t$ **and** $Diag\ t$
shows $Inv\ t\ [\cdot]\ t = Dom\ t$
using *assms Can-and-Diag-implies-Ide Ide-in-Hom* **by** *simp*

The next fact is a syntactic version of the interchange law, for diagonal terms.

lemma *CompDiag-TensorDiag*:
assumes $Diag\ t$ **and** $Diag\ u$ **and** $Diag\ v$ **and** $Diag\ w$
and $Seq\ t\ v$ **and** $Seq\ u\ w$
shows $(t\ [\otimes]\ u)\ [\cdot]\ (v\ [\otimes]\ w) = (t\ [\cdot]\ v)\ [\otimes]\ (u\ [\cdot]\ w)$
proof –
have $\bigwedge u\ v\ w. \llbracket Diag\ t; Diag\ u; Diag\ v; Diag\ w; Seq\ t\ v; Seq\ u\ w \rrbracket \implies$
 $(t\ [\otimes]\ u)\ [\cdot]\ (v\ [\otimes]\ w) = (t\ [\cdot]\ v)\ [\otimes]\ (u\ [\cdot]\ w)$
proof (*induct t, simp-all*)
fix $u\ v\ w$
assume $u: Diag\ u$
assume $v: Diag\ v$
assume $w: Diag\ w$
assume $uw: Seq\ u\ w$
show $Arr\ v \wedge \mathcal{I} = Cod\ v \implies u\ [\cdot]\ (v\ [\otimes]\ w) = v\ [\otimes]\ (u\ [\cdot]\ w)$
using $u\ v\ w\ uw$ **by** (*cases v*) *simp-all*
show $\bigwedge f. \llbracket C.arr\ f; Arr\ v \wedge \langle C.dom\ f \rangle = Cod\ v \rrbracket \implies$

$(\langle f \rangle [\otimes] u) [\cdot] (v [\otimes] w) = (\langle f \rangle [\cdot] v) [\otimes] (u [\cdot] w)$

proof –

fix f

assume $f: C.arr\ f$

assume $1: Arr\ v \wedge \langle C.dom\ f \rangle = Cod\ v$

show $(\langle f \rangle [\otimes] u) [\cdot] (v [\otimes] w) = (\langle f \rangle [\cdot] v) [\otimes] (u [\cdot] w)$

proof –

have $2: v = \langle un-Prim\ v \rangle \wedge C.arr\ (un-Prim\ v)$ **using** $v\ 1$ **by** $(cases\ v)\ simp-all$

have $u = \mathcal{I} \implies ?thesis$

using $v\ w\ uw\ 1\ 2\ Cod.simps(3)\ CompDiag-Cod-Diag\ Dom.simps(2)$

$TensorDiag-Prim\ TensorDiag-term-Unity\ TensorDiag-preserves-Diag(3)$

by $(cases\ w)\ simp-all$

moreover **have** $u \neq \mathcal{I} \implies ?thesis$

proof –

assume $3: u \neq \mathcal{I}$

hence $4: w \neq \mathcal{I}$ **using** $u\ w\ uw$ **by** $(cases\ u,\ simp-all; cases\ w,\ simp-all)$

have $(\langle f \rangle [\otimes] u) [\cdot] (v [\otimes] w) = (\langle f \rangle \otimes u) [\cdot] (v \otimes w)$

proof –

have $\langle f \rangle [\otimes] u = \langle f \rangle \otimes u$

using $u\ f\ 3\ TensorDiag-Diag$ **by** $(cases\ u)\ simp-all$

moreover **have** $v [\otimes] w = v \otimes w$

using $w\ 2\ 4\ TensorDiag-Diag$ **by** $(cases\ v,\ simp-all; cases\ w,\ simp-all)$

ultimately **show** $?thesis$ **by** $simp$

qed

also **have** $5: \dots = (\langle f \rangle [\cdot] v) \otimes (u [\cdot] w)$ **by** $simp$

also **have** $\dots = (\langle f \rangle [\cdot] v) [\otimes] (u [\cdot] w)$

using $f\ u\ w\ uw\ 1\ 2\ 3\ 4\ 5$

$TensorDiag-Diag\ TensorDiag-Prim\ TensorDiag-preserves-Diag(1)$

$CompDiag-preserves-Diag(1)$

by $(metis\ Cod.simps(3)\ Dom.simps(1)\ Dom.simps(3)\ Diag.simps(2))$

finally **show** $?thesis$ **by** $blast$

qed

ultimately **show** $?thesis$ **by** $blast$

qed

fix $t1\ t2$

assume $I2: \bigwedge u\ v\ w. \llbracket Diag\ t2; Diag\ u; Diag\ v; Diag\ w; Arr\ v \wedge Dom\ t2 = Cod\ v; Seq\ u\ w \rrbracket \implies$

$(t2 [\otimes] u) [\cdot] (v [\otimes] w) = (t2 [\cdot] v) [\otimes] (u [\cdot] w)$

assume $t12: Diag\ (t1 \otimes t2)$

have $t1: t1 = \langle un-Prim\ t1 \rangle \wedge C.arr\ (un-Prim\ t1) \wedge Diag\ t1$

using $t12$ **by** $(cases\ t1)\ simp-all$

have $t2: Diag\ t2 \wedge t2 \neq \mathcal{I}$

using $t12$ **by** $(cases\ t1)\ simp-all$

assume $1: Arr\ t1 \wedge Arr\ t2 \wedge Arr\ v \wedge Dom\ t1 \otimes Dom\ t2 = Cod\ v$

show $((t1 \otimes t2) [\otimes] u) [\cdot] (v [\otimes] w) = ((t1 \otimes t2) [\cdot] v) [\otimes] (u [\cdot] w)$

proof –

have $u = \mathcal{I} \implies ?thesis$

using $w\ uw\ TensorDiag-term-Unity\ CompDiag-Cod-Diag$ **by** $(cases\ w)\ simp-all$

moreover have $u \neq \mathcal{I} \implies ?thesis$
proof –
assume $u': u \neq \mathcal{I}$
hence $w': w \neq \mathcal{I}$ **using** $u w uw$ **by** (*cases u; simp; cases w; simp*)
show $?thesis$
using $1 v$
proof (*cases v, simp-all*)
fix $v1 v2$
assume $v12: v = \text{Tensor } v1 v2$
have $v1: v1 = \langle \text{un-Prim } v1 \rangle \wedge C.\text{arr } (\text{un-Prim } v1) \wedge \text{Diag } v1$
using $v v12$ **by** (*cases v1 simp-all*)
have $v2: \text{Diag } v2 \wedge v2 \neq \mathcal{I}$
using $v v12$ **by** (*cases v1 simp-all*)
have $2: v = (\langle \text{un-Prim } v1 \rangle \otimes v2)$
using $v1 v12$ **by** *simp*
show $((t1 \otimes t2) \llbracket \otimes \rrbracket u) \llbracket \cdot \rrbracket ((v1 \otimes v2) \llbracket \otimes \rrbracket w)$
 $= ((t1 \llbracket \cdot \rrbracket v1) \otimes (t2 \llbracket \cdot \rrbracket v2)) \llbracket \otimes \rrbracket (u \llbracket \cdot \rrbracket w)$
proof –
have $3: (t1 \otimes t2) \llbracket \otimes \rrbracket u = t1 \llbracket \otimes \rrbracket (t2 \llbracket \otimes \rrbracket u)$
using $u u'$ **by** (*cases u simp-all*)
have $4: v \llbracket \otimes \rrbracket w = v1 \llbracket \otimes \rrbracket (v2 \llbracket \otimes \rrbracket w)$
using $v w v1 v2 2$ *TensorDiag-assoc TensorDiag-Diag* **by** *metis*
have $((t1 \otimes t2) \llbracket \otimes \rrbracket u) \llbracket \cdot \rrbracket ((v1 \otimes v2) \llbracket \otimes \rrbracket w)$
 $= (t1 \llbracket \otimes \rrbracket (t2 \llbracket \otimes \rrbracket u)) \llbracket \cdot \rrbracket (v1 \llbracket \otimes \rrbracket (v2 \llbracket \otimes \rrbracket w))$
using $3 4 v12$ **by** *simp*
also have $\dots = (t1 \llbracket \cdot \rrbracket v1) \llbracket \otimes \rrbracket ((t2 \llbracket \otimes \rrbracket u) \llbracket \cdot \rrbracket (v2 \llbracket \otimes \rrbracket w))$
proof –
have *is-Tensor* $(t2 \llbracket \otimes \rrbracket u)$
using $t2 u u'$ *not-is-Tensor-TensorDiagE* **by** *auto*
moreover have *is-Tensor* $(v2 \llbracket \otimes \rrbracket w)$
using $v2 v12 w w'$ *not-is-Tensor-TensorDiagE* **by** *auto*
ultimately show $?thesis$
using $u u' v w t1 v1 t12 v12$ *TensorDiag-Prim not-is-Tensor-Unity*
by (*metis (no-types, lifting) CompDiag.simps(2) CompDiag.simps(3)*)
is-Tensor-def
qed
also have $\dots = (t1 \llbracket \cdot \rrbracket v1) \llbracket \otimes \rrbracket (t2 \llbracket \cdot \rrbracket v2) \llbracket \otimes \rrbracket (u \llbracket \cdot \rrbracket w)$
using $u w uw t2 v2 1 2$ *Diag-implies-Arr I2* **by** *fastforce*
also have $\dots = ((t1 \llbracket \cdot \rrbracket v1) \otimes (t2 \llbracket \cdot \rrbracket v2)) \llbracket \otimes \rrbracket (u \llbracket \cdot \rrbracket w)$
proof –
have $u \llbracket \cdot \rrbracket w \neq \text{Unity}$
proof –
have $\text{Arr } v1 \wedge \langle C.\text{dom } (\text{un-Prim } t1) \rangle = \text{Cod } v1$
using $t1 v1 1 2$ **by** (*cases t1, auto*)
thus $?thesis$
using $t1 t2 v1 v2 u w uw u'$ *CompDiag-preserves-Diag*
TensorDiag-preserves-Diag TensorDiag-Prim
by (*metis (mono-tags, lifting) Cod.simps(2) Cod.simps(3)*)
TensorDiag.simps(2) term.distinct(3)

```

    qed
  hence ((t1 [·] v1) ⊗ (t2 [·] v2)) [⊗] (u [·] w)
        = (t1 [·] v1) [⊗] ((t2 [·] v2) [⊗] (u [·] w))
    by (cases u [·] w) simp-all
  thus ?thesis by argo
  qed
  finally show ?thesis by blast
  qed
  qed
  qed
  ultimately show ?thesis by blast
  qed
  qed
  thus ?thesis using assms by blast
  qed

```

The following function reduces an arrow to diagonal form. The precise relationship between a term and its diagonalization is developed below.

```

fun Diagonalize :: 'a term ⇒ 'a term  (⟨[-]⟩)
where [⟨f⟩] = ⟨f⟩
  | [ℐ] = ℐ
  | [t ⊗ u] = [t] [⊗] [u]
  | [t · u] = [t] [·] [u]
  | [ℓ] = [t]
  | [ℓ⁻¹] = [t]
  | [r] = [t]
  | [r⁻¹] = [t]
  | [a[t, u, v]] = ([t] [⊗] [u]) [⊗] [v]
  | [a⁻¹[t, u, v]] = [t] [⊗] ([u] [⊗] [v])

```

lemma *Diag-Diagonalize*:

assumes *Arr t*

shows *Diag [t]* and *Dom [t] = [Dom t]* and *Cod [t] = [Cod t]*

proof –

have $0: Arr\ t \implies Diag\ [t] \wedge Dom\ [t] = [Dom\ t] \wedge Cod\ [t] = [Cod\ t]$

using *TensorDiag-preserves-Diag CompDiag-preserves-Diag TensorDiag-assoc*

apply (*induct t*)

apply *auto*

apply (*metis (full-types)*)

by (*metis (full-types)*)

show *Diag [t]* **using** *assms 0* **by** *blast*

show *Dom [t] = [Dom t]* **using** *assms 0* **by** *blast*

show *Cod [t] = [Cod t]* **using** *assms 0* **by** *blast*

qed

lemma *Diagonalize-in-Hom*:

assumes *Arr t*

shows $[t] \in Hom\ [Dom\ t]\ [Cod\ t]$

using *assms Diag-Diagonalize Diag-implies-Arr* **by** *blast*

lemma *Diagonalize-Dom*:
assumes *Arr t*
shows $\lfloor \text{Dom } t \rfloor = \text{Dom } \lfloor t \rfloor$
using *assms Diagonalize-in-Hom* **by** *simp*

lemma *Diagonalize-Cod*:
assumes *Arr t*
shows $\lfloor \text{Cod } t \rfloor = \text{Cod } \lfloor t \rfloor$
using *assms Diagonalize-in-Hom* **by** *simp*

lemma *Diagonalize-preserves-Ide*:
assumes *Ide a*
shows *Ide* $\lfloor a \rfloor$
proof –
 have *Ide a* \implies *Ide* $\lfloor a \rfloor$
 using *Ide-implies-Arr TensorDiag-preserves-Ide Diag-Diagonalize*
 by (*induct a*) *simp-all*
 thus *?thesis* **using** *assms* **by** *blast*
qed

The diagonalizations of canonical arrows are identities.

lemma *Ide-Diagonalize-Can*:
assumes *Can t*
shows *Ide* $\lfloor t \rfloor$
proof –
 have *Can t* \implies *Ide* $\lfloor t \rfloor$
 using *Can-implies-Arr TensorDiag-preserves-Ide Diag-Diagonalize CompDiag-preserves-Ide*
 TensorDiag-preserves-Diag
 by (*induct t*) *auto*
 thus *?thesis* **using** *assms* **by** *blast*
qed

lemma *Diagonalize-preserves-Can*:
assumes *Can t*
shows *Can* $\lfloor t \rfloor$
using *assms Ide-Diagonalize-Can Ide-implies-Can* **by** *auto*

lemma *Diagonalize-Diag* [*simp*]:
assumes *Diag t*
shows $\lfloor t \rfloor = t$
proof –
 have *Diag t* \implies $\lfloor t \rfloor = t$
 apply (*induct t, simp-all*)
 using *TensorDiag-Prim Diag-TensorE* **by** *metis*
 thus *?thesis* **using** *assms* **by** *blast*
qed

lemma *Diagonalize-Diagonalize* [*simp*]:

assumes $Arr\ t$
shows $\llbracket t \rrbracket = \lfloor t \rfloor$
using *assms Diag-Diagonalize Diagonalize-Diag* **by** *blast*

lemma *Diagonalize-Tensor*:
assumes $Arr\ t$ **and** $Arr\ u$
shows $\lfloor t \otimes u \rfloor = \llbracket \lfloor t \rfloor \otimes \lfloor u \rfloor \rrbracket$
using *assms Diagonalize-Diagonalize* **by** *simp*

lemma *Diagonalize-Tensor-Unity-Arr* [*simp*]:
assumes $Arr\ u$
shows $\llbracket \mathcal{I} \otimes u \rrbracket = \llbracket u \rrbracket$
using *assms* **by** *simp*

lemma *Diagonalize-Tensor-Arr-Unity* [*simp*]:
assumes $Arr\ t$
shows $\llbracket t \otimes \mathcal{I} \rrbracket = \llbracket t \rrbracket$
using *assms* **by** *simp*

lemma *Diagonalize-Tensor-Prim-Arr* [*simp*]:
assumes $arr\ f$ **and** $Arr\ u$ **and** $\llbracket u \rrbracket \neq Unity$
shows $\llbracket \langle f \rangle \otimes u \rrbracket = \langle \llbracket f \rrbracket \otimes \llbracket u \rrbracket \rangle$
using *assms* **by** *simp*

lemma *Diagonalize-Tensor-Tensor*:
assumes $Arr\ t$ **and** $Arr\ u$ **and** $Arr\ v$
shows $\llbracket (t \otimes u) \otimes v \rrbracket = \llbracket \llbracket t \rrbracket \otimes (\llbracket u \rrbracket \otimes \llbracket v \rrbracket) \rrbracket$
using *assms Diag-Diagonalize Diagonalize-Diagonalize* **by** (*simp add: TensorDiag-assoc*)

lemma *Diagonalize-Comp-Cod-Arr*:
assumes $Arr\ t$
shows $\llbracket Cod\ t \cdot t \rrbracket = \llbracket t \rrbracket$
proof –
have $Arr\ t \implies \llbracket Cod\ t \cdot t \rrbracket = \llbracket t \rrbracket$
using *C.comp-cod-arr*
apply (*induct t, simp-all*)
using *CompDiag-TensorDiag Arr-implies-Ide-Cod Ide-in-Hom Diag-Diagonalize*
Diagonalize-in-Hom
apply *simp*
using *CompDiag-preserves-Diag CompDiag-Cod-Diag Diag-Diagonalize*
apply *metis*
using *CompDiag-TensorDiag Arr-implies-Ide-Cod Ide-in-Hom TensorDiag-in-Hom*
TensorDiag-preserves-Diag Diag-Diagonalize Diagonalize-in-Hom TensorDiag-assoc
by *simp-all*
thus *?thesis* **using** *assms* **by** *blast*

qed

lemma *Diagonalize-Comp-Arr-Dom*:
assumes $Arr\ t$

```

shows  $[t \cdot \text{Dom } t] = [t]$ 
proof -
  have  $\text{Arr } t \implies [t \cdot \text{Dom } t] = [t]$ 
    by (metis CompDiag-Diag-Dom Diag-Diagonalize(1-2) Diagonalize.simps(4))
  thus ?thesis using assms by blast
qed

lemma Diagonalize-Inv:
assumes Can t
shows  $[\text{Inv } t] = \text{Inv } [t]$ 
proof -
  have  $\text{Can } t \implies [\text{Inv } t] = \text{Inv } [t]$ 
  proof (induct t, simp-all)
    fix  $u v$ 
    assume I1:  $[\text{Inv } u] = \text{Inv } [u]$ 
    assume I2:  $[\text{Inv } v] = \text{Inv } [v]$ 
    show  $\text{Can } u \wedge \text{Can } v \implies \text{Inv } [u] [\otimes] \text{Inv } [v] = \text{Inv } ([u] [\otimes] [v])$ 
      using Inv-TensorDiag Diag-Diagonalize Can-implies-Arr Diagonalize-preserves-Can
        I1 I2
      by simp
    show  $\text{Can } u \wedge \text{Can } v \wedge \text{Dom } u = \text{Cod } v \implies \text{Inv } [v] [\cdot] \text{Inv } [u] = \text{Inv } ([u] [\cdot] [v])$ 
      using Inv-CompDiag Diag-Diagonalize Can-implies-Arr Diagonalize-in-Hom
        Diagonalize-preserves-Can I1 I2
      by simp
    fix  $w$ 
    assume I3:  $[\text{Inv } w] = \text{Inv } [w]$ 
    assume uvw:  $\text{Can } u \wedge \text{Can } v \wedge \text{Can } w$ 
    show  $\text{Inv } [u] [\otimes] (\text{Inv } [v] [\otimes] \text{Inv } [w]) = \text{Inv } (([u] [\otimes] [v]) [\otimes] [w])$ 
      using uvw I1 I2 I3
      Inv-TensorDiag Diag-Diagonalize Can-implies-Arr Diagonalize-preserves-Can
      TensorDiag-preserves-Diag TensorDiag-preserves-Can TensorDiag-assoc
      by simp
    show  $(\text{Inv } [u] [\otimes] \text{Inv } [v]) [\otimes] \text{Inv } [w] = \text{Inv } ([u] [\otimes] ([v] [\otimes] [w]))$ 
      by (simp add: Can-implies-Arr Ide-Diagonalize-Can TensorDiag-assoc
        TensorDiag-preserves-Diag(1) TensorDiag-preserves-Ide Diag-Diagonalize(1) uvw)
  qed
thus ?thesis using assms by blast
qed

```

Our next objective is to begin making the connection, to be completed in a subsequent section, between arrows and their diagonalizations. To summarize, an arrow t and its diagonalization $[t]$ are opposite sides of a square whose other sides are certain canonical terms $\text{Dom } t \downarrow \in \text{Hom } (\text{Dom } t) [\text{Dom } t]$ and $\text{Cod } t \downarrow \in \text{Hom } (\text{Cod } t) [\text{Cod } t]$, where $\text{Dom } t \downarrow$ and $\text{Cod } t \downarrow$ are defined by the function *red* below. The coherence theorem amounts to the statement that every such square commutes when the formal terms involved are evaluated in the evident way in any monoidal category.

Function *red* defined below takes an identity term a to a canonical arrow $a \downarrow \in \text{Hom } a [a]$. The auxiliary function *red2* takes a pair (a, b) of diagonal identity terms and produces a canonical arrow $a \downarrow b \in \text{Hom } (a \otimes b) [a \otimes b]$. The canonical arrow $a \downarrow$

amounts to a “parallel innermost reduction” from a to $\lfloor a \rfloor$, where the reduction steps are canonical arrows that involve the unitors and associator only in their uninverted forms. In general, a parallel innermost reduction from a will not be unique: at some points there is a choice available between left and right unitors and at other points there are choices between unitors and associators. These choices are inessential, and the ordering of the clauses in the function definitions below resolves them in an arbitrary way. What is more important is having chosen an innermost reduction, which is what allows us to write these definitions in structurally recursive form.

The essence of coherence is that the axioms for a monoidal category allow us to prove that any reduction from a to $\lfloor a \rfloor$ is equivalent (under evaluation of terms) to a parallel innermost reduction. The problematic cases are terms of the form $((a \otimes b) \otimes c) \otimes d$, which present a choice between an inner and outer reduction that lead to terms with different structures. It is of course the pentagon axiom that ensures the confluence (under evaluation) of the two resulting paths.

Although simple in appearance, the structurally recursive definitions below were difficult to get right even after I started to understand what I was doing. I wish I could have just written them down straightaway. If so, then I could have avoided laboriously constructing and then throwing away thousands of lines of proof text that used a non-structural, “operational” approach to defining a reduction from a to $\lfloor a \rfloor$.

```

fun red2                                (infixr  $\langle \Downarrow \rangle$  53)
where  $\mathcal{I} \Downarrow a = \mathbf{1}[a]$ 
      |  $\langle f \rangle \Downarrow \mathcal{I} = \mathbf{r}[\langle f \rangle]$ 
      |  $\langle f \rangle \Downarrow a = \langle f \rangle \otimes a$ 
      |  $(a \otimes b) \Downarrow \mathcal{I} = \mathbf{r}[a \otimes b]$ 
      |  $(a \otimes b) \Downarrow c = (a \Downarrow \lfloor b \otimes c \rfloor) \cdot (a \otimes (b \Downarrow c)) \cdot \mathbf{a}[a, b, c]$ 
      |  $a \Downarrow b = \text{undefined}$ 

```

```

fun red                                  ( $\langle \cdot \Downarrow \rangle$  [56] 56)
where  $\mathcal{I} \Downarrow = \mathcal{I}$ 
      |  $\langle f \rangle \Downarrow = \langle f \rangle$ 
      |  $(a \otimes b) \Downarrow = (\text{if } \text{Diag } (a \otimes b) \text{ then } a \otimes b \text{ else } (\lfloor a \rfloor \Downarrow \lfloor b \rfloor) \cdot (a \Downarrow \otimes b \Downarrow))$ 
      |  $a \Downarrow = \text{undefined}$ 

```

```

lemma red-Diag [simp]:
assumes Diag a
shows  $a \Downarrow = a$ 
  using assms by (cases a) simp-all

```

```

lemma red2-Diag:
assumes Diag (a  $\otimes$  b)
shows  $a \Downarrow b = a \otimes b$ 
proof –
  have a:  $a = \langle \text{un-Prim } a \rangle$ 
    using assms Diag-TensorE by metis
  have b:  $\text{Diag } b \wedge b \neq \mathcal{I}$ 
    using assms Diag-TensorE by metis
  show ?thesis using a b

```

apply (*cases b*)
apply *simp-all*
apply (*metis red2.simps(3)*)
by (*metis red2.simps(4)*)
qed

lemma *Can-red2*:

assumes *Ide a* **and** *Diag a* **and** *Ide b* **and** *Diag b*

shows *Can (a ↓ b)*

and $a \Downarrow b \in \text{Hom} (a \otimes b) [a \otimes b]$

proof –

have $0: \bigwedge b. \llbracket \text{Ide } a \wedge \text{Diag } a; \text{Ide } b \wedge \text{Diag } b \rrbracket \implies$
 $\text{Can } (a \Downarrow b) \wedge a \Downarrow b \in \text{Hom} (a \otimes b) [a \otimes b]$

proof (*induct a, simp-all*)

fix *b*

show $\text{Ide } b \wedge \text{Diag } b \implies \text{Can } b \wedge \text{Dom } b = b \wedge \text{Cod } b = b$

using *Ide-implies-Can Ide-in-Hom Diagonalize-Diag* **by** *auto*

fix *f*

show $\llbracket C.\text{ide } f \wedge C.\text{arr } f; \text{Ide } b \wedge \text{Diag } b \rrbracket \implies$

$\text{Can } (\langle f \rangle \Downarrow b) \wedge \text{Arr } (\langle f \rangle \Downarrow b) \wedge \text{Dom } (\langle f \rangle \Downarrow b) = \langle f \rangle \otimes b \wedge$
 $\text{Cod } (\langle f \rangle \Downarrow b) = \langle f \rangle [\otimes] b$

using *Ide-implies-Can Ide-in-Hom* **by** (*cases b; auto*)

next

fix *a b c*

assume *ab*: $\text{Ide } a \wedge \text{Ide } b \wedge \text{Diag } (\text{Tensor } a \ b)$

assume *c*: $\text{Ide } c \wedge \text{Diag } c$

assume *I1*: $\bigwedge c. \llbracket \text{Diag } a; \text{Ide } c \wedge \text{Diag } c \rrbracket \implies$

$\text{Can } (a \Downarrow c) \wedge \text{Arr } (a \Downarrow c) \wedge \text{Dom } (a \Downarrow c) = a \otimes c \wedge$
 $\text{Cod } (a \Downarrow c) = a [\otimes] c$

assume *I2*: $\bigwedge c. \llbracket \text{Diag } b; \text{Ide } c \wedge \text{Diag } c \rrbracket \implies$

$\text{Can } (b \Downarrow c) \wedge \text{Arr } (b \Downarrow c) \wedge \text{Dom } (b \Downarrow c) = b \otimes c \wedge$
 $\text{Cod } (b \Downarrow c) = b [\otimes] c$

show $\text{Can } ((a \otimes b) \Downarrow c) \wedge \text{Arr } ((a \otimes b) \Downarrow c) \wedge$

$\text{Dom } ((a \otimes b) \Downarrow c) = (a \otimes b) \otimes c \wedge$

$\text{Cod } ((a \otimes b) \Downarrow c) = ([a] [\otimes] [b]) [\otimes] c$

proof –

have *a*: $\text{Diag } a \wedge \text{Ide } a$

using *ab Diag-TensorE* **by** *blast*

have *b*: $\text{Diag } b \wedge \text{Ide } b$

using *ab Diag-TensorE* **by** *blast*

have *c* = $\mathcal{I} \implies ?thesis$

proof –

assume *1*: $c = \mathcal{I}$

have *2*: $(a \otimes b) \Downarrow c = \mathbf{r}[a \otimes b]$

using *1* **by** *simp*

have *3*: $\text{Can } (a \Downarrow b) \wedge \text{Arr } (a \Downarrow b) \wedge \text{Dom } (a \Downarrow b) = a \otimes b \wedge \text{Cod } (a \Downarrow b) = a \otimes b$

using *a b ab 1 2 I1 Diagonalize-Diag Diagonalize.simps(3)* **by** *metis*

hence *4*: $\text{Seq } (a \Downarrow b) \mathbf{r}[a \otimes b]$

using *ab*

by (*metis* (*mono-tags*, *lifting*) *Arr.simps*(7) *Cod.simps*(3) *Cod.simps*(7)
Diag-implies-Arr Ide-in-Hom mem-Collect-eq)
 have $Can ((a \otimes b) \Downarrow c)$
 using 1 2 3 4 *ab* by (*simp add: Ide-implies-Can*)
 moreover have $Dom ((a \otimes b) \Downarrow c) = (a \otimes b) \otimes c$
 using 1 2 3 4 *a b ab I1 Ide-in-Hom TensorDiag-preserves-Diag* by *simp*
 moreover have $Cod ((a \otimes b) \Downarrow c) = \lfloor (a \otimes b) \otimes c \rfloor$
 using 1 2 3 4 *ab* using *Diagonalize-Diag* by *fastforce*
 ultimately show *?thesis* using *Can-implies-Arr* by (*simp add: 1 ab*)
 qed
 moreover have $c \neq \mathcal{I} \implies ?thesis$
 proof –
 assume 1: $c \neq \mathcal{I}$
 have 2: $(a \otimes b) \Downarrow c = (a \Downarrow \lfloor b \otimes c \rfloor) \cdot (a \otimes b \Downarrow c) \cdot \mathbf{a}[a, b, c]$
 using 1 *a b ab c* by (*cases c; simp*)
 have 3: $Can (a \Downarrow \lfloor b \otimes c \rfloor) \wedge Dom (a \Downarrow \lfloor b \otimes c \rfloor) = a \otimes \lfloor b \otimes c \rfloor \wedge$
 $Cod (a \Downarrow \lfloor b \otimes c \rfloor) = \lfloor a \otimes (b \otimes c) \rfloor$
 proof –
 have $Can (a \Downarrow \lfloor b \otimes c \rfloor) \wedge Dom (a \Downarrow \lfloor b \otimes c \rfloor) = a \otimes \lfloor b \otimes c \rfloor \wedge$
 $Cod (a \Downarrow \lfloor b \otimes c \rfloor) = \lfloor a \otimes \lfloor b \otimes c \rfloor \rfloor$
 using *a c ab 1 2 I1 Diag-implies-Arr Diag-Diagonalize(1)*
Diagonalize-preserves-Ide TensorDiag-preserves-Ide
TensorDiag-preserves-Diag(1)
 by *auto*
 moreover have $\lfloor a \otimes \lfloor b \otimes c \rfloor \rfloor = \lfloor a \otimes (b \otimes c) \rfloor$
 using *ab c Diagonalize-Tensor Diagonalize-Diagonalize Diag-implies-Arr*
 by (*metis Arr.simps(3) Diagonalize.simps(3)*)
 ultimately show *?thesis* by *metis*
 qed
 have 4: $Can (b \Downarrow c) \wedge Dom (b \Downarrow c) = b \otimes c \wedge Cod (b \Downarrow c) = \lfloor b \otimes c \rfloor$
 using *b c ab 1 2 I2* by *simp*
 hence $Can (a \otimes (b \Downarrow c)) \wedge Dom (a \otimes (b \Downarrow c)) = a \otimes (b \otimes c) \wedge$
 $Cod (a \otimes (b \Downarrow c)) = a \otimes \lfloor b \otimes c \rfloor$
 using *ab Ide-implies-Can Ide-in-Hom* by *force*
 moreover have $\lfloor a \otimes \lfloor b \otimes c \rfloor \rfloor = \lfloor a \otimes b \rfloor \lfloor \otimes \rfloor \lfloor c \rfloor$
 proof –
 have $\lfloor a \otimes \lfloor b \otimes c \rfloor \rfloor = a \lfloor \otimes \rfloor (b \lfloor \otimes \rfloor c)$
 using *a b c 4*
 by (*metis Arr-implies-Ide-Dom Can-implies-Arr Ide-implies-Arr*
Diag-Diagonalize(1) Diagonalize.simps(3) Diagonalize-Diag)
 also have $\dots = (a \lfloor \otimes \rfloor b) \lfloor \otimes \rfloor c$
 using *a b ab c TensorDiag-assoc* by *metis*
 also have $\dots = \lfloor a \otimes b \rfloor \lfloor \otimes \rfloor \lfloor c \rfloor$
 using *a b c* by (*metis Diagonalize.simps(3) Diagonalize-Diag*)
 finally show *?thesis* by *blast*
 qed
 moreover have $Can \mathbf{a}[a, b, c] \wedge Dom \mathbf{a}[a, b, c] = (a \otimes b) \otimes c \wedge$
 $Cod \mathbf{a}[a, b, c] = a \otimes (b \otimes c)$
 using *ab c Ide-implies-Can Ide-in-Hom* by *auto*

ultimately show *?thesis*
using *c 2 3 4 Diagonalize-Diagonalize Ide-implies-Can*
Diagonalize-Diag Arr-implies-Ide-Dom Can-implies-Arr
by (*metis Can.simps(4) Cod.simps(4) Dom.simps(4) Diagonalize.simps(3)*)
qed
ultimately show *?thesis by blast*
qed
show $Can (a \Downarrow b)$ **using** *assms 0 by blast*
show $a \Downarrow b \in Hom (a \otimes b) [a \otimes b]$ **using** *0 assms by blast*
qed

lemma *red2-in-Hom*:
assumes *Ide a and Diag a and Ide b and Diag b*
shows $a \Downarrow b \in Hom (a \otimes b) [a \otimes b]$
using *assms Can-red2 Can-implies-Arr by simp*

lemma *Can-red*:

assumes *Ide a*

shows $Can (a \Downarrow)$ **and** $a \Downarrow \in Hom a [a]$

proof –

have $0: Ide a \implies Can (a \Downarrow) \wedge a \Downarrow \in Hom a [a]$

proof (*induct a, simp-all*)

fix $b c$

assume $b: Can (b \Downarrow) \wedge Arr (b \Downarrow) \wedge Dom (b \Downarrow) = b \wedge Cod (b \Downarrow) = [b]$

assume $c: Can (c \Downarrow) \wedge Arr (c \Downarrow) \wedge Dom (c \Downarrow) = c \wedge Cod (c \Downarrow) = [c]$

assume $bc: Ide b \wedge Ide c$

show ($Diag (b \otimes c) \longrightarrow$

$Can b \wedge Can c \wedge Dom b = b \wedge Dom c = c \wedge Cod b \otimes Cod c = [b] [\otimes] [c] \wedge$

$(\neg Diag (b \otimes c) \longrightarrow$

$Can ([b] \Downarrow [c]) \wedge Dom ([b] \Downarrow [c]) = [b] \otimes [c] \wedge Arr ([b] \Downarrow [c]) \wedge$

$Dom ([b] \Downarrow [c]) = [b] \otimes [c] \wedge Cod ([b] \Downarrow [c]) = [b] [\otimes] [c]$)

proof

show $Diag (b \otimes c) \longrightarrow$

$Can b \wedge Can c \wedge Dom b = b \wedge Dom c = c \wedge Cod b \otimes Cod c = [b] [\otimes] [c]$

using *bc Diag-TensorE Ide-implies-Can Inv-preserves-Can(2)*

CompDiag-Ide-Diag Inv-Ide Diagonalize.simps(3) Diagonalize-Diag

by (*metis CompDiag-Inv-Can*)

show $\neg Diag (b \otimes c) \longrightarrow$

$Can ([b] \Downarrow [c]) \wedge Dom ([b] \Downarrow [c]) = [b] \otimes [c] \wedge Arr ([b] \Downarrow [c]) \wedge$

$Dom ([b] \Downarrow [c]) = [b] \otimes [c] \wedge Cod ([b] \Downarrow [c]) = [b] [\otimes] [c]$

using *b c bc Ide-in-Hom Ide-implies-Can Can-red2 Diag-Diagonalize*

Diagonalize-preserves-Ide TensorDiag-preserves-Diag TensorDiag-preserves-Ide

by *force*

qed

qed

show $Can (a \Downarrow)$ **using** *assms 0 by blast*

show $a \Downarrow \in Hom a [a]$ **using** *assms 0 by blast*

qed

```

lemma red-in-Hom:
assumes Ide a
shows  $a \downarrow \in \text{Hom } a \lfloor a \rfloor$ 
using assms Can-red Can-implies-Arr by simp

lemma Diagonalize-red [simp]:
assumes Ide a
shows  $\lfloor a \downarrow \rfloor = \lfloor a \rfloor$ 
using assms Can-red Ide-Diagonalize-Can Diagonalize-in-Hom Ide-in-Hom by fastforce

lemma Diagonalize-red2 [simp]:
assumes Ide a and Ide b and Diag a and Diag b
shows  $\lfloor a \downarrow b \rfloor = \lfloor a \otimes b \rfloor$ 
using assms Can-red2 Ide-Diagonalize-Can Diagonalize-in-Hom [of a \downarrow b]
red2-in-Hom Ide-in-Hom
by simp

end

```

2.7 Coherence

If D is a monoidal category, then a functor $V: C \rightarrow D$ extends in an evident way to an evaluation map that interprets each formal arrow of the monoidal language of C as an arrow of D .

```

locale evaluation-map =
  monoidal-language C +
  monoidal-category D T  $\alpha$   $\iota$  +
  V: functor C D V
for  $C :: 'c \text{ comp}$  (infixr  $\langle \cdot_C \rangle$  55)
and  $D :: 'd \text{ comp}$  (infixr  $\langle \cdot \rangle$  55)
and  $T :: 'd * 'd \Rightarrow 'd$ 
and  $\alpha :: 'd * 'd * 'd \Rightarrow 'd$ 
and  $\iota :: 'd$ 
and  $V :: 'c \Rightarrow 'd$ 
begin

  no-notation C.in-hom ( $\langle \langle - : - \rightarrow - \rangle \rangle$ )

  notation unity ( $\langle \mathcal{I} \rangle$ )
  notation runit ( $\langle r[-] \rangle$ )
  notation lunit ( $\langle l[-] \rangle$ )
  notation assoc' ( $\langle a^{-1}[-, -, -] \rangle$ )
  notation runit' ( $\langle r^{-1}[-] \rangle$ )
  notation lunit' ( $\langle l^{-1}[-] \rangle$ )

  primrec eval ::  $'c \text{ term} \Rightarrow 'd$  ( $\langle \lfloor - \rfloor \rangle$ )
  where  $\lfloor \langle f \rangle \rfloor = V f$ 

```

```

|  $\{\mathcal{I}\} = \mathcal{I}$ 
|  $\{t \otimes u\} = \{t\} \otimes \{u\}$ 
|  $\{t \cdot u\} = \{t\} \cdot \{u\}$ 
|  $\{\mathbf{1}[t]\} = \mathbf{1} \{t\}$ 
|  $\{\mathbf{1}^{-1}[t]\} = \mathbf{1}' \{t\}$ 
|  $\{\mathbf{r}[t]\} = \varrho \{t\}$ 
|  $\{\mathbf{r}^{-1}[t]\} = \varrho' \{t\}$ 
|  $\{\mathbf{a}[t, u, v]\} = \alpha (\{t\}, \{u\}, \{v\})$ 
|  $\{\mathbf{a}^{-1}[t, u, v]\} = \alpha' (\{t\}, \{u\}, \{v\})$ 

```

Identity terms evaluate to identities of D and evaluation preserves domain and codomain.

lemma *ide-eval-Ide* [*simp*]:
shows $Ide\ t \implies ide\ \{t\}$
by (*induct t, auto*)

lemma *eval-in-hom*:
shows $Arr\ t \implies \langle \{t\} : \{Dom\ t\} \rightarrow \{Cod\ t\} \rangle$
apply (*induct t*)
apply *auto*[4]
apply *fastforce*

proof –

fix $t\ u\ v$

assume I : $Arr\ t \implies \langle \{t\} : \{Dom\ t\} \rightarrow \{Cod\ t\} \rangle$

show $Arr\ \mathbf{1}^{-1}[t] \implies \langle \{\mathbf{1}^{-1}[t]\} : \{Dom\ \mathbf{1}^{-1}[t]\} \rightarrow \{Cod\ \mathbf{1}^{-1}[t]\} \rangle$

using $I\ arr\text{-}dom\text{-iff}\text{-}arr$ [*of* $\{t\}$] **by** *force*

show $Arr\ \mathbf{r}[t] \implies \langle \{\mathbf{r}[t]\} : \{Dom\ \mathbf{r}[t]\} \rightarrow \{Cod\ \mathbf{r}[t]\} \rangle$

using $I\ arr\text{-}cod\text{-iff}\text{-}arr$ [*of* $\{t\}$] **by** *force*

show $Arr\ \mathbf{r}^{-1}[t] \implies \langle \{\mathbf{r}^{-1}[t]\} : \{Dom\ \mathbf{r}^{-1}[t]\} \rightarrow \{Cod\ \mathbf{r}^{-1}[t]\} \rangle$

using $I\ arr\text{-}dom\text{-iff}\text{-}arr$ [*of* $\{t\}$] **by** *force*

assume $I1$: $Arr\ t \implies \langle \{t\} : \{Dom\ t\} \rightarrow \{Cod\ t\} \rangle$

assume $I2$: $Arr\ u \implies \langle \{u\} : \{Dom\ u\} \rightarrow \{Cod\ u\} \rangle$

assume $I3$: $Arr\ v \implies \langle \{v\} : \{Dom\ v\} \rightarrow \{Cod\ v\} \rangle$

show $Arr\ \mathbf{a}[t, u, v] \implies \langle \{\mathbf{a}[t, u, v]\} : \{Dom\ \mathbf{a}[t, u, v]\} \rightarrow \{Cod\ \mathbf{a}[t, u, v]\} \rangle$

proof –

assume 1 : $Arr\ \mathbf{a}[t, u, v]$

have t : $\langle \{t\} : dom\ \{t\} \rightarrow cod\ \{t\} \rangle$ **using** $1\ I1$ **by** *auto*

have u : $\langle \{u\} : dom\ \{u\} \rightarrow cod\ \{u\} \rangle$ **using** $1\ I2$ **by** *auto*

have v : $\langle \{v\} : dom\ \{v\} \rightarrow cod\ \{v\} \rangle$ **using** $1\ I3$ **by** *auto*

have $\{\mathbf{a}[t, u, v]\} = (\{t\} \otimes \{u\} \otimes \{v\}) \cdot \mathbf{a}[dom\ \{t\}, dom\ \{u\}, dom\ \{v\}]$

using $t\ u\ v\ \alpha\text{-simp}$ [*of* $\{t\}\ \{u\}\ \{v\}$] **by** *auto*

moreover **have** $\langle (\{t\} \otimes \{u\} \otimes \{v\}) \cdot \mathbf{a}[dom\ \{t\}, dom\ \{u\}, dom\ \{v\}] :$

$(dom\ \{t\} \otimes dom\ \{u\}) \otimes dom\ \{v\} \rightarrow cod\ \{t\} \otimes cod\ \{u\} \otimes cod\ \{v\} \rangle$

using $t\ u\ v$ **by** (*elim in-homE, auto*)

moreover **have** $\{Dom\ t\} = dom\ \{t\} \wedge \{Dom\ u\} = dom\ \{u\} \wedge \{Dom\ v\} = dom\ \{v\} \wedge$

$\{Cod\ t\} = cod\ \{t\} \wedge \{Cod\ u\} = cod\ \{u\} \wedge \{Cod\ v\} = cod\ \{v\}$

using $1\ I1\ I2\ I3$ **by** *auto*

ultimately **show** $\langle \{\mathbf{a}[t, u, v]\} : \{Dom\ \mathbf{a}[t, u, v]\} \rightarrow \{Cod\ \mathbf{a}[t, u, v]\} \rangle$

by *simp*

qed
show $\text{Arr } \mathbf{a}^{-1}[t, u, v] \implies \llbracket \mathbf{a}^{-1}[t, u, v] \rrbracket : \llbracket \text{Dom } \mathbf{a}^{-1}[t, u, v] \rrbracket \rightarrow \llbracket \text{Cod } \mathbf{a}^{-1}[t, u, v] \rrbracket$
proof –
assume $1: \text{Arr } \mathbf{a}^{-1}[t, u, v]$
have $t: \llbracket t \rrbracket : \text{dom } \llbracket t \rrbracket \rightarrow \text{cod } \llbracket t \rrbracket$ **using** $1\ I1$ **by** *auto*
have $u: \llbracket u \rrbracket : \text{dom } \llbracket u \rrbracket \rightarrow \text{cod } \llbracket u \rrbracket$ **using** $1\ I2$ **by** *auto*
have $v: \llbracket v \rrbracket : \text{dom } \llbracket v \rrbracket \rightarrow \text{cod } \llbracket v \rrbracket$ **using** $1\ I3$ **by** *auto*
have $\llbracket \mathbf{a}^{-1}[t, u, v] \rrbracket = ((\llbracket t \rrbracket \otimes \llbracket u \rrbracket) \otimes \llbracket v \rrbracket) \cdot \mathbf{a}^{-1}[\text{dom } \llbracket t \rrbracket, \text{dom } \llbracket u \rrbracket, \text{dom } \llbracket v \rrbracket]$
using $1\ I1\ I2\ I3\ \alpha'$ -*simp* [of $\llbracket t \rrbracket\ \llbracket u \rrbracket\ \llbracket v \rrbracket$] **by** *auto*
moreover **have** $\llbracket ((\llbracket t \rrbracket \otimes \llbracket u \rrbracket) \otimes \llbracket v \rrbracket) \cdot \mathbf{a}^{-1}[\text{dom } \llbracket t \rrbracket, \text{dom } \llbracket u \rrbracket, \text{dom } \llbracket v \rrbracket] \rrbracket :$
 $\text{dom } \llbracket t \rrbracket \otimes \text{dom } \llbracket u \rrbracket \otimes \text{dom } \llbracket v \rrbracket \rightarrow (\text{cod } \llbracket t \rrbracket \otimes \text{cod } \llbracket u \rrbracket) \otimes \text{cod } \llbracket v \rrbracket$
using $t\ u\ v$ *assoc'-in-hom* [of $\text{dom } \llbracket t \rrbracket\ \text{dom } \llbracket u \rrbracket\ \text{dom } \llbracket v \rrbracket$]
by (*elim in-homE*, *auto*)
moreover **have** $\llbracket \text{Dom } t \rrbracket = \text{dom } \llbracket t \rrbracket \wedge \llbracket \text{Dom } u \rrbracket = \text{dom } \llbracket u \rrbracket \wedge \llbracket \text{Dom } v \rrbracket = \text{dom } \llbracket v \rrbracket \wedge$
 $\llbracket \text{Cod } t \rrbracket = \text{cod } \llbracket t \rrbracket \wedge \llbracket \text{Cod } u \rrbracket = \text{cod } \llbracket u \rrbracket \wedge \llbracket \text{Cod } v \rrbracket = \text{cod } \llbracket v \rrbracket$
using $1\ I1\ I2\ I3$ **by** *auto*
ultimately show $\llbracket \mathbf{a}^{-1}[t, u, v] \rrbracket : \llbracket \text{Dom } \mathbf{a}^{-1}[t, u, v] \rrbracket \rightarrow \llbracket \text{Cod } \mathbf{a}^{-1}[t, u, v] \rrbracket$
by *simp*
qed
qed

lemma *arr-eval* [*simp*]:
assumes $\text{Arr } f$
shows $\text{arr } \llbracket f \rrbracket$
using *assms eval-in-hom* **by** *auto*

lemma *dom-eval* [*simp*]:
assumes $\text{Arr } f$
shows $\text{dom } \llbracket f \rrbracket = \llbracket \text{Dom } f \rrbracket$
using *assms eval-in-hom* **by** *auto*

lemma *cod-eval* [*simp*]:
assumes $\text{Arr } f$
shows $\text{cod } \llbracket f \rrbracket = \llbracket \text{Cod } f \rrbracket$
using *assms eval-in-hom* **by** *auto*

lemma *eval-Prim* [*simp*]:
assumes $C.\text{arr } f$
shows $\llbracket \langle f \rangle \rrbracket = V f$
by *simp*

lemma *eval-Tensor* [*simp*]:
assumes $\text{Arr } t$ **and** $\text{Arr } u$
shows $\llbracket t \otimes u \rrbracket = \llbracket t \rrbracket \otimes \llbracket u \rrbracket$
using *assms eval-in-hom* **by** *auto*

lemma *eval-Comp* [*simp*]:
assumes $\text{Arr } t$ **and** $\text{Arr } u$ **and** $\text{Dom } t = \text{Cod } u$
shows $\llbracket t \cdot u \rrbracket = \llbracket t \rrbracket \cdot \llbracket u \rrbracket$

using *assms* **by** *simp*

lemma *eval-Lunit* [*simp*]:

assumes *Arr t*

shows $\{\mathbf{l}[t]\} = \mathbf{l}[\{\text{Cod } t\}] \cdot (\mathcal{I} \otimes \{t\})$

using *assms lunit-naturality* [of $\{t\}$] **by** *simp*

lemma *eval-Lunit'* [*simp*]:

assumes *Arr t*

shows $\{\mathbf{l}^{-1}[t]\} = \mathbf{l}^{-1}[\{\text{Cod } t\}] \cdot \{t\}$

using *assms lunit'-naturality* [of $\{t\}$] *l'.map-simp* [of $\{t\}$] *l-ide-simp*
Arr-implies-Ide-Cod

by *simp*

lemma *eval-Runit* [*simp*]:

assumes *Arr t*

shows $\{\mathbf{r}[t]\} = \mathbf{r}[\{\text{Cod } t\}] \cdot (\{t\} \otimes \mathcal{I})$

using *assms runit-naturality* [of $\{t\}$] **by** *simp*

lemma *eval-Runit'* [*simp*]:

assumes *Arr t*

shows $\{\mathbf{r}^{-1}[t]\} = \mathbf{r}^{-1}[\{\text{Cod } t\}] \cdot \{t\}$

using *assms runit'-naturality* [of $\{t\}$] *q'.map-simp* [of $\{t\}$] *q-ide-simp*
Arr-implies-Ide-Cod

by *simp*

lemma *eval-Assoc* [*simp*]:

assumes *Arr t* **and** *Arr u* **and** *Arr v*

shows $\{\mathbf{a}[t, u, v]\} = \mathbf{a}[\text{cod } \{t\}, \text{cod } \{u\}, \text{cod } \{v\}] \cdot ((\{t\} \otimes \{u\}) \otimes \{v\})$

using *assms a.naturality2* [of $(\{t\}, \{u\}, \{v\})$] **by** *auto*

lemma *eval-Assoc'* [*simp*]:

assumes *Arr t* **and** *Arr u* **and** *Arr v*

shows $\{\mathbf{a}^{-1}[t, u, v]\} = \mathbf{a}^{-1}[\text{cod } \{t\}, \text{cod } \{u\}, \text{cod } \{v\}] \cdot (\{t\} \otimes \{u\} \otimes \{v\})$

using *assms a'-simp* [of $\{t\}$ $\{u\}$ $\{v\}$] *assoc'-naturality* [of $\{t\}$ $\{u\}$ $\{v\}$]

by *simp*

The following are conveniences for the case of identity arguments to avoid having to get rid of the extra identities that are introduced by the general formulas above.

lemma *eval-Lunit-Ide* [*simp*]:

assumes *Ide a*

shows $\{\mathbf{l}[a]\} = \mathbf{l}[\{a\}]$

using *assms comp-cod-arr* **by** *simp*

lemma *eval-Lunit'-Ide* [*simp*]:

assumes *Ide a*

shows $\{\mathbf{l}^{-1}[a]\} = \mathbf{l}^{-1}[\{a\}]$

using *assms comp-cod-arr* **by** *simp*

lemma *eval-Runit-Ide* [*simp*]:
assumes *Ide a*
shows $\{\mathbf{r}[a]\} = \mathbf{r}\{\{a\}\}$
using *assms comp-cod-arr* **by** *simp*

lemma *eval-Runit'-Ide* [*simp*]:
assumes *Ide a*
shows $\{\mathbf{r}^{-1}[a]\} = \mathbf{r}^{-1}\{\{a\}\}$
using *assms comp-cod-arr* **by** *simp*

lemma *eval-Assoc-Ide* [*simp*]:
assumes *Ide a* **and** *Ide b* **and** *Ide c*
shows $\{\mathbf{a}[a, b, c]\} = \mathbf{a}\{\{a\}, \{b\}, \{c\}\}$
using *assms* **by** *simp*

lemma *eval-Assoc'-Ide* [*simp*]:
assumes *Ide a* **and** *Ide b* **and** *Ide c*
shows $\{\mathbf{a}^{-1}[a, b, c]\} = \mathbf{a}^{-1}\{\{a\}, \{b\}, \{c\}\}$
using *assms α' -ide-simp* **by** *simp*

Canonical arrows evaluate to isomorphisms in D , and formal inverses evaluate to inverses in D .

lemma *iso-eval-Can*:
shows *Can t* \implies *iso* $\{t\}$
using *Can-implies-Arr* *l'.preserves-iso* *q'.preserves-iso* *alpha.preserves-iso* *alpha'.preserves-iso*
Arr-implies-Ide-Dom
by (*induct t*) *auto*

lemma *eval-Inv-Can*:
shows *Can t* \implies $\{\mathbf{Inv} t\} = \mathbf{inv} \{t\}$
apply (*induct t*)
using *iso-eval-Can inv-comp* *Can-implies-Arr*
apply *auto*[4]

proof –
fix *t*
assume *I*: *Can t* \implies $\{\mathbf{Inv} t\} = \mathbf{inv} \{t\}$
show *Can* $\mathbf{1}[t]$ \implies $\{\mathbf{Inv} \mathbf{1}[t]\} = \mathbf{inv} \{\mathbf{1}[t]\}$
using *I* *l'.naturality2* [*of inv* $\{t\}$] *iso-eval-Can l-ide-simp iso-is-arr*
comp-cod-arr inv-comp
by *simp*
show *Can* $\mathbf{r}[t]$ \implies $\{\mathbf{Inv} \mathbf{r}[t]\} = \mathbf{inv} \{\mathbf{r}[t]\}$
using *I* *q'.naturality2* [*of inv* $\{t\}$] *iso-eval-Can q-ide-simp iso-is-arr*
comp-cod-arr inv-comp
by *simp*
show *Can* $\mathbf{1}^{-1}[t]$ \implies $\{\mathbf{Inv} \mathbf{1}^{-1}[t]\} = \mathbf{inv} \{\mathbf{1}^{-1}[t]\}$
proof –
assume *t*: *Can* $\mathbf{1}^{-1}[t]$
hence *1*: *iso* $\{t\}$ **using** *iso-eval-Can* **by** *simp*
have *inv* $\{\mathbf{1}^{-1}[t]\} = \mathbf{inv} (\mathbf{1}' \{t\})$

using t by *simp*
 also have $\dots = \text{inv } (1^{-1}[\text{cod } \{t\}] \cdot \{t\})$
 using 1 *l'.naturality2* [of $\{t\}$] *l'-ide-simp iso-is-arr* by *auto*
 also have $\dots = \{ \text{Inv } 1^{-1}[t] \}$
 using t *I 1 iso-is-arr inv-comp* by *auto*
 finally show *?thesis* by *simp*
 qed
 show $\text{Can } \mathbf{r}^{-1}[t] \implies \{ \text{Inv } \mathbf{r}^{-1}[t] \} = \text{inv } \{ \mathbf{r}^{-1}[t] \}$
 proof –
 assume t : $\text{Can } \mathbf{r}^{-1}[t]$
 hence 1 : $\text{iso } \{t\}$ using *iso-eval-Can* by *simp*
 have $\text{inv } \{ \mathbf{r}^{-1}[t] \} = \text{inv } (\varrho' \{t\})$
 using t by *simp*
 also have $\dots = \text{inv } (\mathbf{r}^{-1}[\text{cod } \{t\}] \cdot \{t\})$
 using 1 *ϱ'.naturality2* [of $\{t\}$] *ϱ'-ide-simp iso-is-arr* by *auto*
 also have $\dots = \{ \text{Inv } \mathbf{r}^{-1}[t] \}$
 using t *I 1 iso-is-arr inv-comp* by *auto*
 finally show *?thesis* by *simp*
 qed
 next
 fix $t u v$
 assume $I1$: $\text{Can } t \implies \{ \text{Inv } t \} = \text{inv } \{t\}$
 assume $I2$: $\text{Can } u \implies \{ \text{Inv } u \} = \text{inv } \{u\}$
 assume $I3$: $\text{Can } v \implies \{ \text{Inv } v \} = \text{inv } \{v\}$
 show $\text{Can } \mathbf{a}[t, u, v] \implies \{ \text{Inv } \mathbf{a}[t, u, v] \} = \text{inv } \{ \mathbf{a}[t, u, v] \}$
 proof –
 assume tuv : $\text{Can } \mathbf{a}[t, u, v]$
 have t : $\text{iso } \{t\}$ using tuv *iso-eval-Can* by *auto*
 have u : $\text{iso } \{u\}$ using tuv *iso-eval-Can* by *auto*
 have v : $\text{iso } \{v\}$ using tuv *iso-eval-Can* by *auto*
 have $\{ \text{Inv } \mathbf{a}[t, u, v] \} = \alpha' (\text{inv } \{t\}, \text{inv } \{u\}, \text{inv } \{v\})$
 using tuv $I1$ $I2$ $I3$ by *simp*
 also have $\dots = \text{inv } (\mathbf{a}[\text{cod } \{t\}, \text{cod } \{u\}, \text{cod } \{v\}] \cdot ((\{t\} \otimes \{u\}) \otimes \{v\}))$
 using $t u v$ α' -*simp iso-is-arr inv-comp* by *auto*
 also have $\dots = \text{inv } ((\{t\} \otimes \{u\} \otimes \{v\}) \cdot \mathbf{a}[\text{dom } \{t\}, \text{dom } \{u\}, \text{dom } \{v\}])$
 using $t u v$ *iso-is-arr assoc-naturality* by *simp*
 also have $\dots = \text{inv } \{ \mathbf{a}[t, u, v] \}$
 using $t u v$ *iso-is-arr α-simp* [of $\{t\}$ $\{u\}$ $\{v\}$] by *simp*
 finally show *?thesis* by *simp*
 qed
 show $\text{Can } \mathbf{a}^{-1}[t, u, v] \implies \{ \text{Inv } \mathbf{a}^{-1}[t, u, v] \} = \text{inv } \{ \mathbf{a}^{-1}[t, u, v] \}$
 proof –
 assume tuv : $\text{Can } \mathbf{a}^{-1}[t, u, v]$
 have t : $\text{iso } \{t\}$ using tuv *iso-eval-Can* by *auto*
 have u : $\text{iso } \{u\}$ using tuv *iso-eval-Can* by *auto*
 have v : $\text{iso } \{v\}$ using tuv *iso-eval-Can* by *auto*
 have $\{ \text{Inv } \mathbf{a}^{-1}[t, u, v] \} = \alpha (\text{inv } \{t\}, \text{inv } \{u\}, \text{inv } \{v\})$
 using tuv $I1$ $I2$ $I3$ by *simp*
 also have $\dots = (\text{inv } \{t\} \otimes \text{inv } \{u\} \otimes \text{inv } \{v\}) \cdot \mathbf{a}[\text{cod } \{t\}, \text{cod } \{u\}, \text{cod } \{v\}]$


```

    using t u v iso-is-arr  $\alpha$ -simp [of inv {t} inv {u} inv {v}] by simp
  also have ... = inv (a-1[cod {t}, cod {u}, cod {v}] · ({t} ⊗ {u} ⊗ {v}))
    using t u v iso-is-arr inv-comp by auto
  also have ... = inv ((({t} ⊗ {u}) ⊗ {v}) · a-1[dom {t}, dom {u}, dom {v}])
    using t u v iso-is-arr assoc'-naturality by simp
  also have ... = inv {a-1[t, u, v]}
    using t u v iso-is-arr  $\alpha'$ -simp by auto
  finally show ?thesis by blast
qed
qed

```

The operation $[\cdot]$ evaluates to composition in D .

lemma *eval-CompDiag*:

assumes *Diag t* and *Diag u* and *Seq t u*

shows $\{t [\cdot] u\} = \{t\} \cdot \{u\}$

proof –

```

  have  $\bigwedge u. [\text{Diag } t; \text{Diag } u; \text{Seq } t u] \implies \{t [\cdot] u\} = \{t\} \cdot \{u\}$ 
    using eval-in-hom comp-cod-arr

```

proof (*induct t, simp-all*)

fix $u f$

assume $u: \text{Diag } u$

assume $f: C.\text{arr } f$

assume $1: \text{Arr } u \wedge \langle C.\text{dom } f \rangle = \text{Cod } u$

show $\{\langle f \rangle [\cdot] u\} = V f \cdot \{u\}$

using $f u 1 \text{ as-nat-trans.preserves-comp-2}$ **by** (*cases u; simp*)

next

fix $u v w$

```

  assume I1:  $\bigwedge u. [\text{Diag } v; \text{Diag } u; \text{Arr } u \wedge \text{Dom } v = \text{Cod } u] \implies$ 
     $\{v [\cdot] u\} = \{v\} \cdot \{u\}$ 

```

```

  assume I2:  $\bigwedge u. [\text{Diag } w; \text{Diag } u; \text{Arr } u \wedge \text{Dom } w = \text{Cod } u] \implies$ 
     $\{w [\cdot] u\} = \{w\} \cdot \{u\}$ 

```

assume $vw: \text{Diag } (\text{Tensor } v w)$

have $v: \text{Diag } v \wedge v = \text{Prim } (\text{un-Prim } v)$

using vw **by** (*simp add: Diag-TensorE*)

have $w: \text{Diag } w$

using vw **by** (*simp add: Diag-TensorE*)

assume $u: \text{Diag } u$

assume $1: \text{Arr } v \wedge \text{Arr } w \wedge \text{Arr } u \wedge \text{Dom } v \otimes \text{Dom } w = \text{Cod } u$

show $\{(v \otimes w) [\cdot] u\} = (\{v\} \otimes \{w\}) \cdot \{u\}$

using $u 1 \text{ eval-in-hom CompDiag-in-Hom}$

proof (*cases u, simp-all*)

fix $x y$

assume $3: u = x \otimes y$

assume $4: \text{Arr } v \wedge \text{Arr } w \wedge \text{Dom } v = \text{Cod } x \wedge \text{Dom } w = \text{Cod } y$

have $x: \text{Diag } x$

using $u 1 3 \text{ Diag-TensorE}$ [*of x y*] **by** *simp*

have $y: \text{Diag } y$

using $u x 1 3 \text{ Diag-TensorE}$ [*of x y*] **by** *simp*

show $\{v [\cdot] x\} \otimes \{w [\cdot] y\} = (\{v\} \otimes \{w\}) \cdot (\{x\} \otimes \{y\})$

```

    using v w x y 4 I1 I2 CompDiag-in-Hom eval-in-hom Diag-implies-Arr interchange
    by auto
  qed
  qed
  thus ?thesis using assms by blast
  qed

```

For identity terms a and b , the reduction $(a \otimes b)\downarrow$ factors (under evaluation in D) into the parallel reduction $a\downarrow \otimes b\downarrow$, followed by a reduction of its codomain $[a] \downarrow [b]$.

```

lemma eval-red-Tensor:
assumes Ide a and Ide b
shows  $\{(a \otimes b)\downarrow\} = \{[a] \downarrow [b]\} \cdot (\{a\downarrow\} \otimes \{b\downarrow\})$ 
proof -
  have Diag  $(a \otimes b) \implies ?thesis$ 
    using assms Can-red2 Ide-implies-Arr red-Diag
      Diagonalize-Diag red2-Diag Can-implies-Arr iso-eval-Can iso-is-arr
    apply simp
    using Diag-TensorE eval-Tensor Diagonalize-Diag Diag-implies-Arr red-Diag
      tensor-preserves-ide ide-eval-Ide dom-eval comp-arr-dom
    by metis
  moreover have  $\neg \text{Diag } (a \otimes b) \implies ?thesis$ 
    using assms Can-red2 by (simp add: Can-red(1) iso-eval-Can)
  ultimately show ?thesis by blast
  qed

```

```

lemma eval-red2-Diag-Unity:
assumes Ide a and Diag a
shows  $\{a \downarrow \mathcal{I}\} = \mathbf{r}[\{a\}]$ 
  using assms tensor-preserves-ide  $g$ -ide-simp unitor-coincidence unit-in-hom comp-cod-arr
  by (cases a, auto)

```

Define a formal arrow t to be “coherent” if the square formed by t , $[t]$ and the reductions $Dom\ t\downarrow$ and $Cod\ t\downarrow$ commutes under evaluation in D . We will show that all formal arrows are coherent. Since the diagonalizations of canonical arrows are identities, a corollary is that parallel canonical arrows have equal evaluations.

```

abbreviation coherent
where coherent  $t \equiv \{Cod\ t\downarrow\} \cdot \{t\} = \{[t]\} \cdot \{Dom\ t\downarrow\}$ 

```

Diagonal arrows are coherent, since for such arrows t the reductions $Dom\ t\downarrow$ and $Cod\ t\downarrow$ are identities.

```

lemma Diag-implies-coherent:
assumes Diag t
shows coherent t
  using assms Diag-implies-Arr Arr-implies-Ide-Dom Arr-implies-Ide-Cod
    Dom-preserves-Diag Cod-preserves-Diag Diagonalize-Diag red-Diag
    comp-arr-dom comp-cod-arr
  by simp

```

The evaluation of a coherent arrow t has a canonical factorization in D into the evaluations of a reduction $Dom\ t\downarrow$, diagonalization $[t]$, and inverse reduction $Inv\ (Cod\ t\downarrow)$.

\downarrow). This will later allow us to use the term $Inv (Cod \downarrow) \cdot [t] \cdot Dom \downarrow$ as a normal form for t .

lemma canonical-factorization:

assumes $Arr\ t$

shows $coherent\ t \longleftrightarrow \{t\} = inv\ \{Cod\ \downarrow\} \cdot \{[t]\} \cdot \{Dom\ \downarrow\}$

proof

assume $1: coherent\ t$

have $inv\ \{Cod\ \downarrow\} \cdot \{[t]\} \cdot \{Dom\ \downarrow\} = inv\ \{Cod\ \downarrow\} \cdot \{Cod\ \downarrow\} \cdot \{t\}$

using 1 **by** *simp*

also have $\dots = (inv\ \{Cod\ \downarrow\} \cdot \{Cod\ \downarrow\}) \cdot \{t\}$

using *comp-assoc* **by** *simp*

also have $\dots = \{t\}$

using *assms 1 red-in-Hom inv-in-hom Arr-implies-Ide-Cod Can-red iso-eval-Can comp-cod-arr Ide-in-Hom inv-is-inverse*

by (*simp add: comp-inv-arr*)

finally show $\{t\} = inv\ \{Cod\ \downarrow\} \cdot \{[t]\} \cdot \{Dom\ \downarrow\}$ **by** *simp*

next

assume $1: \{t\} = inv\ \{Cod\ \downarrow\} \cdot \{[t]\} \cdot \{Dom\ \downarrow\}$

hence $\{Cod\ \downarrow\} \cdot \{t\} = \{Cod\ \downarrow\} \cdot inv\ \{Cod\ \downarrow\} \cdot \{[t]\} \cdot \{Dom\ \downarrow\}$ **by** *simp*

also have $\dots = (\{Cod\ \downarrow\} \cdot inv\ \{Cod\ \downarrow\}) \cdot \{[t]\} \cdot \{Dom\ \downarrow\}$

using *comp-assoc* **by** *simp*

also have $\dots = \{[t]\} \cdot \{Dom\ \downarrow\}$

using *assms 1 red-in-Hom Arr-implies-Ide-Cod Can-red iso-eval-Can inv-is-inverse*

Diagonalize-in-Hom comp-arr-inv comp-cod-arr Arr-implies-Ide-Dom Diagonal-

ize-in-Hom

by *auto*

finally show $coherent\ t$ **by** *blast*

qed

A canonical arrow is coherent if and only if its formal inverse is.

lemma Can-implies-coherent-iff-coherent-Inv:

assumes $Can\ t$

shows $coherent\ t \longleftrightarrow coherent\ (Inv\ t)$

proof

have $1: \bigwedge t. Can\ t \implies coherent\ t \implies coherent\ (Inv\ t)$

proof –

fix t

assume $Can\ t$

hence $t: Can\ t \wedge Arr\ t \wedge Ide\ (Dom\ t) \wedge Ide\ (Cod\ t) \wedge$

$arr\ \{t\} \wedge iso\ \{t\} \wedge inverse-arrows\ \{t\}\ (inv\ \{t\}) \wedge$

$Can\ [t] \wedge Arr\ [t] \wedge arr\ \{[t]\} \wedge iso\ \{[t]\} \wedge [t] \in Hom\ [Dom\ t]\ [Cod\ t] \wedge$

$inverse-arrows\ \{[t]\}\ (inv\ \{[t]\}) \wedge Inv\ t \in Hom\ (Cod\ t)\ (Dom\ t)$

using *assms Can-implies-Arr Arr-implies-Ide-Dom Arr-implies-Ide-Cod iso-eval-Can inv-is-inverse Diagonalize-in-Hom Diagonalize-preserves-Can Inv-in-Hom*

by *simp*

assume *coh: coherent\ t*

have $\{Cod\ (Inv\ t)\downarrow\} \cdot \{Inv\ t\} = (inv\ \{[t]\} \cdot \{[t]\}) \cdot \{Cod\ (Inv\ t)\downarrow\} \cdot \{Inv\ t\}$

using t *red-in-Hom comp-cod-arr comp-inv-arr*

by (*simp add: canonical-factorization coh Diagonalize-preserves-Can*)

```

    <Can t> inv-is-inverse)
  also have ... = inv {↓t} · (↓Cod t↓ · ↓t) · inv {t}
    using t eval-Inv-Can coh comp-assoc by auto
  also have ... = {↓Inv t} · ↓Dom (Inv t)↓
    using t Diagonalize-Inv eval-Inv-Can comp-arr-inv red-in-Hom comp-arr-dom comp-assoc
    by auto
  finally show coherent (Inv t) by blast
qed
show coherent t ⇒ coherent (Inv t) using assms 1 by simp
show coherent (Inv t) ⇒ coherent t
proof -
  assume coherent (Inv t)
  hence coherent (Inv (Inv t))
    using assms 1 Inv-preserves-Can by blast
  thus ?thesis using assms by simp
qed
qed

```

Some special cases of coherence are readily dispatched.

lemma *coherent-Unity*:
shows *coherent* \mathcal{I}
 by *simp*

lemma *coherent-Prim*:
assumes *Arr* $\langle f \rangle$
shows *coherent* $\langle f \rangle$
 using *assms* by *simp*

lemma *coherent-Lunit-Ide*:
assumes *Ide* a
shows *coherent* $\mathbb{I}[a]$
proof -
 have a : $Ide\ a \wedge Arr\ a \wedge Dom\ a = a \wedge Cod\ a = a \wedge$
 $ide\ \{a\} \wedge ide\ \{\llbracket a \rrbracket\} \wedge \{a\downarrow} \in hom\ \{a\}\ \{\llbracket a \rrbracket\}$
 using *assms* *Ide-implies-Arr* *Ide-in-Hom* *Diagonalize-preserves-Ide* *red-in-Hom* by *auto*
 thus ?thesis
 using *a* *lunit-naturality* [of $\{a\downarrow}$] *comp-cod-arr* by *auto*
qed

lemma *coherent-Runit-Ide*:
assumes *Ide* a
shows *coherent* $\mathbf{r}[a]$
proof -
 have a : $Ide\ a \wedge Arr\ a \wedge Dom\ a = a \wedge Cod\ a = a \wedge$
 $ide\ \{a\} \wedge ide\ \{\llbracket a \rrbracket\} \wedge \{a\downarrow} \in hom\ \{a\}\ \{\llbracket a \rrbracket\}$
 using *assms* *Ide-implies-Arr* *Ide-in-Hom* *Diagonalize-preserves-Ide* *red-in-Hom*
 by *auto*
 have $\{Cod\ \mathbf{r}[a]\downarrow} \cdot \{\mathbf{r}[a]\} = \{a\downarrow} \cdot \mathbf{r}\{\llbracket a \rrbracket\}$
 using *a* *runit-in-hom* *comp-cod-arr* by *simp*

also have $\dots = r[\{[a]\}] \cdot (\{a\downarrow\} \otimes \mathcal{I})$
using *a eval-Runit runit-naturality [of $\{red\ a\}]$ by auto*
also have $\dots = \{[r[a]]\} \cdot \{Dom\ r[a]\downarrow\}$
proof –
have $\neg Diag\ (a \otimes \mathcal{I})$ **by** (*cases a; simp*)
thus *?thesis*
using *a comp-cod-arr red2-in-Hom eval-red2-Diag-Unity Diag-Diagonalize*
Diagonalize-preserves-Ide
by *auto*
qed
finally show *?thesis* **by** *blast*
qed

lemma *coherent-Lunit'-Ide:*
assumes *Ide a*
shows *coherent $\mathbf{l}^{-1}[a]$*
using *assms Ide-implies-Can coherent-Lunit-Ide*
Can-implies-coherent-iff-coherent-Inv [of Lunit a] by simp

lemma *coherent-Runit'-Ide:*
assumes *Ide a*
shows *coherent $\mathbf{r}^{-1}[a]$*
using *assms Ide-implies-Can coherent-Runit-Ide*
Can-implies-coherent-iff-coherent-Inv [of Runit a] by simp

To go further, we need the next result, which is in some sense the crux of coherence: For diagonal identities a , b , and c , the reduction $((a \llbracket \otimes \rrbracket b) \Downarrow c) \cdot ((a \Downarrow b) \otimes c)$ from $(a \otimes b) \otimes c$ that first reduces the subterm $a \otimes b$ and then reduces the result, is equivalent under evaluation in D to the reduction that first applies the associator $\mathbf{a}[a, b, c]$ and then applies the reduction $(a \Downarrow b \llbracket \otimes \rrbracket c) \cdot (a \otimes b \Downarrow c)$ from $a \otimes b \otimes c$. The triangle and pentagon axioms are used in the proof.

lemma *coherence-key-fact:*
assumes *Ide a \wedge Diag a and Ide b \wedge Diag b and Ide c \wedge Diag c*
shows $\{(a \llbracket \otimes \rrbracket b) \Downarrow c\} \cdot (\{a \Downarrow b\} \otimes \{c\})$
 $= (\{a \Downarrow (b \llbracket \otimes \rrbracket c)\}) \cdot (\{a\} \otimes \{b \Downarrow c\}) \cdot \mathbf{a}[\{a\}, \{b\}, \{c\}]$
proof –
have $b = \mathcal{I} \implies ?thesis$
using *assms not-is-Tensor-TensorDiagE eval-red2-Diag-Unity triangle*
comp-cod-arr comp-assoc
by *simp*

The triangle is used!

moreover have $c = \mathcal{I} \implies ?thesis$
using *assms TensorDiag-preserves-Diag TensorDiag-preserves-Ide*
not-is-Tensor-TensorDiagE eval-red2-Diag-Unity
red2-in-Hom runit-tensor runit-naturality [of $\{a \Downarrow b\}]$ comp-assoc
by *simp*
moreover have $\llbracket b \neq \mathcal{I}; c \neq \mathcal{I} \rrbracket \implies ?thesis$
proof –

assume $b': b \neq \mathcal{I}$
hence $b: Ide\ b \wedge Diag\ b \wedge Arr\ b \wedge b \neq \mathcal{I} \wedge$
 $ide\ \{\!\{b\}\!\} \wedge arr\ \{\!\{b\}\!\} \wedge \lfloor b \rfloor = b \wedge b \downarrow = b \wedge Dom\ b = b \wedge Cod\ b = b$
using *assms* *Diagonalize-preserves-Ide Ide-in-Hom* **by** *simp*
assume $c': c \neq \mathcal{I}$
hence $c: Ide\ c \wedge Diag\ c \wedge Arr\ c \wedge c \neq \mathcal{I} \wedge$
 $ide\ \{\!\{c\}\!\} \wedge arr\ \{\!\{c\}\!\} \wedge \lfloor c \rfloor = c \wedge c \downarrow = c \wedge Dom\ c = c \wedge Cod\ c = c$
using *assms* *Diagonalize-preserves-Ide Ide-in-Hom* **by** *simp*
have $\bigwedge a. Ide\ a \wedge Diag\ a \implies$
 $\{\!\{a\ \lfloor \otimes \rfloor\ b\}\!\} \downarrow c \} \cdot (\{\!\{a\}\!\} \downarrow b \} \otimes \{\!\{c\}\!\})$
 $= (\{\!\{a\}\!\} \downarrow (b\ \lfloor \otimes \rfloor\ c) \} \cdot (\{\!\{a\}\!\} \otimes \{\!\{b\}\!\} \downarrow c \}) \cdot a[\{\!\{a\}\!\}, \{\!\{b\}\!\}, \{\!\{c\}\!\}]$
proof –
fix $a :: 'c\ term$
show $Ide\ a \wedge Diag\ a \implies$
 $\{\!\{a\ \lfloor \otimes \rfloor\ b\}\!\} \downarrow c \} \cdot (\{\!\{a\}\!\} \downarrow b \} \otimes \{\!\{c\}\!\})$
 $= (\{\!\{a\}\!\} \downarrow (b\ \lfloor \otimes \rfloor\ c) \} \cdot (\{\!\{a\}\!\} \otimes \{\!\{b\}\!\} \downarrow c \}) \cdot a[\{\!\{a\}\!\}, \{\!\{b\}\!\}, \{\!\{c\}\!\}]$
apply (*induct* a)
using $b\ c\ TensorDiag-in-Hom$ **apply** *simp-all*
proof –
show $\{\!\{b\}\!\} \downarrow c \} \cdot (\{\!\{b\}\!\} \cdot 1[\{\!\{b\}\!\} \otimes \{\!\{c\}\!\}])$
 $= ((\{\!\{b\}\!\} \lfloor \otimes \rfloor\ c) \} \cdot 1[\{\!\{b\}\!\} \lfloor \otimes \rfloor\ c]) \cdot (\mathcal{I} \otimes \{\!\{b\}\!\} \downarrow c) \cdot a[\mathcal{I}, \{\!\{b\}\!\}, \{\!\{c\}\!\}]$
proof –
have $\{\!\{b\}\!\} \lfloor \otimes \rfloor\ c \} \cdot (1[\{\!\{b\}\!\} \lfloor \otimes \rfloor\ c]) \cdot (\mathcal{I} \otimes \{\!\{b\}\!\} \downarrow c) \cdot a[\mathcal{I}, \{\!\{b\}\!\}, \{\!\{c\}\!\}] =$
 $\{\!\{b\}\!\} \lfloor \otimes \rfloor\ c \} \cdot (\{\!\{b\}\!\} \downarrow c \} \cdot 1[\{\!\{b\}\!\} \otimes \{\!\{c\}\!\}]) \cdot a[\mathcal{I}, \{\!\{b\}\!\}, \{\!\{c\}\!\}]$
using $b\ c\ red2-in-Hom\ lunit-naturality$ [of $\{\!\{b\}\!\} \downarrow c \}$] **by** *simp*
thus *?thesis*
using $b\ c\ red2-in-Hom\ lunit-tensor\ comp-arr-dom\ comp-cod-arr\ comp-assoc$ **by** *simp*
qed
show $\bigwedge f. C.ide\ f \wedge C.arr\ f \implies$
 $\{\!\{(\langle f \rangle \otimes b)\}\!\} \downarrow c \} \cdot (\{\!\{f\}\!\} \downarrow b \} \otimes \{\!\{c\}\!\})$
 $= (\{\!\{f\}\!\} \downarrow (b\ \lfloor \otimes \rfloor\ c) \} \cdot (Vf \otimes \{\!\{b\}\!\} \downarrow c)) \cdot a[Vf, \{\!\{b\}\!\}, \{\!\{c\}\!\}]$
proof –
fix f
assume $f: C.ide\ f \wedge C.arr\ f$
show $\{\!\{(\langle f \rangle \otimes b)\}\!\} \downarrow c \} \cdot (\{\!\{f\}\!\} \downarrow b \} \otimes \{\!\{c\}\!\})$
 $= (\{\!\{f\}\!\} \downarrow (b\ \lfloor \otimes \rfloor\ c) \} \cdot (Vf \otimes \{\!\{b\}\!\} \downarrow c)) \cdot a[Vf, \{\!\{b\}\!\}, \{\!\{c\}\!\}]$
proof –
have $\{\!\{(\langle f \rangle \otimes b)\}\!\} \downarrow c \} \cdot (\{\!\{f\}\!\} \downarrow b \} \otimes \{\!\{c\}\!\})$
 $= ((Vf \otimes \{\!\{b\}\!\} \lfloor \otimes \rfloor\ c) \} \cdot (Vf \otimes \{\!\{b\}\!\} \downarrow c)) \cdot a[Vf, \{\!\{b\}\!\}, \{\!\{c\}\!\}] \cdot$
 $((Vf \otimes \{\!\{b\}\!\}) \otimes \{\!\{c\}\!\})$
proof –
have $\{\!\{f\}\!\} \downarrow b \} = Vf \otimes \{\!\{b\}\!\}$
using *assms* $f\ b\ c\ red2-Diag$ **by** *simp*
moreover **have** $\{\!\{f\}\!\} \downarrow (b\ \lfloor \otimes \rfloor\ c) \} = Vf \otimes \{\!\{b\}\!\} \lfloor \otimes \rfloor\ c \}$
proof –
have *is-Tensor* $(b\ \lfloor \otimes \rfloor\ c)$
using *assms* $b\ c\ not-is-Tensor-TensorDiagE$ **by** *blast*
thus *?thesis*
using *assms* $f\ b\ c\ red2-Diag\ TensorDiag-preserves-Diag(1)$

```

    by (cases b [⊗] c; simp)
  qed
  ultimately show ?thesis
    using assms b c by (cases c, simp-all)
  qed
  also have ... = ((V f ⊗ {b [⊗] c}) · (V f ⊗ {b ↓ c})) · a[V f, {b}, {c}]
    using b c f TensorDiag-in-Hom red2-in-Hom comp-arr-dom comp-cod-arr
    by simp
  also have ... = ({f} ↓ (b [⊗] c)) · (V f ⊗ {b ↓ c}) · a[V f, {b}, {c}]
    using b c f Ide-implies-Arr TensorDiag-preserves-Ide not-is-Tensor-TensorDiagE
    by (cases b [⊗] c, simp-all; blast)
  finally show ?thesis by blast
  qed
  qed
  fix d e
  assume I: Diag e ⇒ ({e [⊗] b} ↓ c) · ({e ↓ b} ⊗ {c})
    = ({e ↓ b [⊗] c}) · ({e} ⊗ {b ↓ c}) · a[{e}, {b}, {c}]
  assume de: Ide d ∧ Ide e ∧ Diag (d ⊗ e)
  show {((d ⊗ e) [⊗] b) ↓ c} · ({(d ⊗ e) ↓ b} ⊗ {c})
    = ({(d ⊗ e) ↓ (b [⊗] c)}) · (({d} ⊗ {e}) ⊗ {b ↓ c}) · a[{d} ⊗ {e}, {b}, {c}]
  proof -
    let ?f = un-Prim d
    have is-Prim d
      using de by (cases d, simp-all)
    hence d = ⟨?f⟩ ∧ C.ide ?f
      using de by (cases d, simp-all)
    hence d: Ide d ∧ Arr d ∧ Dom d = d ∧ Cod d = d ∧ Diag d ∧
      d = ⟨?f⟩ ∧ C.ide ?f ∧ ide {d} ∧ arr {d}
      using de ide-eval-Ide Ide-implies-Arr Diag-Diagonalize(1) Ide-in-Hom
      Diag-TensorE [of d e]
    by simp
    have Diag e ∧ e ≠  $\mathcal{I}$ 
      using de Diag-TensorE by metis
    hence e: Ide e ∧ Arr e ∧ Dom e = e ∧ Cod e = e ∧ Diag e ∧
      e ≠  $\mathcal{I}$  ∧ ide {e} ∧ arr {e}
      using de Ide-in-Hom by simp
    have 1: is-Tensor (e [⊗] b) ∧ is-Tensor (b [⊗] c) ∧ is-Tensor (e [⊗] (b [⊗] c))
      using b c e de not-is-Tensor-TensorDiagE TensorDiag-preserves-Diag
      not-is-Tensor-TensorDiagE [of e b [⊗] c]
    by auto
    have {((d ⊗ e) [⊗] b) ↓ c} · ({(d ⊗ e) ↓ b} ⊗ {c})
      = (({d} ⊗ {e [⊗] b} [⊗] c}) · ({d} ⊗ {e [⊗] b} ↓ c}) ·
        a[{d}, {e [⊗] b}, {c}] ·
        (({d} ⊗ {e [⊗] b}) · ({d} ⊗ {e ↓ b}) · a[{d}, {e}, {b}] ⊗ {c})
  proof -
    have {((d ⊗ e) [⊗] b) ↓ c}
      = ({d} ⊗ {e [⊗] b} [⊗] c}) · ({d} ⊗ {e [⊗] b} ↓ c}) ·
        a[{d}, {e [⊗] b}, {c}]
  proof -

```

have $((d \otimes e) \lfloor \otimes \rfloor b) \Downarrow c = (d \otimes (e \lfloor \otimes \rfloor b)) \Downarrow c$
using $b\ c\ d\ e\ de\ 1\ TensorDiag-Diag\ TensorDiag-preserves-Diag\ TensorDiag-assoc$
 $TensorDiag-Prim\ not-is-Tensor-Utity$
by *metis*
also have $\dots = (d \Downarrow ((e \lfloor \otimes \rfloor b) \lfloor \otimes \rfloor c)) \cdot (d \otimes ((e \lfloor \otimes \rfloor b) \Downarrow c)) \cdot$
 $a[d, e \lfloor \otimes \rfloor b, c]$
using $c\ d\ 1$ **by** (*cases c*) *simp-all*
also have $\dots = (d \otimes ((e \lfloor \otimes \rfloor b) \lfloor \otimes \rfloor c)) \cdot (d \otimes ((e \lfloor \otimes \rfloor b) \Downarrow c)) \cdot$
 $a[d, e \lfloor \otimes \rfloor b, c]$
by (*metis 1 Diagonalize-Diag TensorDiag-assoc TensorDiag-preserves-Diag(1)*)
 $b\ c\ d\ e\ is-Tensor-def\ red2.simps(4)$
finally show *?thesis*
using $b\ c\ d\ e\ TensorDiag-in-Hom\ red2-in-Hom\ TensorDiag-preserves-Diag$
 $TensorDiag-preserves-Ide$
by *simp*
qed
moreover have $\{\{d \otimes e\} \Downarrow b\}$
 $= (\{\{d\} \otimes \{\{e \lfloor \otimes \rfloor b\}\}) \cdot (\{\{d\} \otimes \{\{e \Downarrow b\}\}) \cdot a[\{\{d\}\}, \{\{e\}\}, \{\{b\}\}]$
proof –
have $(d \otimes e) \Downarrow b = (d \Downarrow (e \lfloor \otimes \rfloor b)) \cdot (d \otimes (e \Downarrow b)) \cdot a[d, e, b]$
using $b\ c\ d\ e\ de\ 1\ TensorDiag-Prim\ Diagonalize-Diag$
by (*cases b*) *simp-all*
also have $\dots = (d \otimes (e \lfloor \otimes \rfloor b)) \cdot (d \otimes (e \Downarrow b)) \cdot a[d, e, b]$
using $b\ d\ e\ 1\ TensorDiag-preserves-Diag\ red2-Diag$
by (*metis Diag.simps(3) de term.disc(12)*)
finally have $(d \otimes e) \Downarrow b = (d \otimes (e \lfloor \otimes \rfloor b)) \cdot (d \otimes (e \Downarrow b)) \cdot a[d, e, b]$
by *simp*
thus *?thesis using b d e eval-in-hom TensorDiag-in-Hom red2-in-Hom by simp*
qed
ultimately show *?thesis by argo*
qed
also have $\dots = (\{\{d\} \otimes \{\{e \lfloor \otimes \rfloor b\} \Downarrow c\}\}) \cdot a[\{\{d\}\}, \{\{e \lfloor \otimes \rfloor b\}\}, \{\{c\}\}] \cdot$
 $(\{\{d\} \otimes \{\{e \Downarrow b\}\}\} \otimes \{\{c\}\}) \cdot (a[\{\{d\}\}, \{\{e\}\}, \{\{b\}\}] \otimes \{\{c\}\})$
using $b\ c\ d\ e\ red2-in-Hom\ TensorDiag-preserves-Ide$
 $TensorDiag-preserves-Diag\ interchange\ comp-cod-arr\ comp-assoc$
by *simp*
also have $\dots = (\{\{d\} \otimes \{\{e \lfloor \otimes \rfloor b\} \Downarrow c\}\}) \cdot (\{\{d\} \otimes (\{\{e \Downarrow b\}\} \otimes \{\{c\}\})\}) \cdot$
 $a[\{\{d\}\}, \{\{e\} \otimes \{\{b\}\}, \{\{c\}\}] \cdot (a[\{\{d\}\}, \{\{e\}\}, \{\{b\}\}] \otimes \{\{c\}\})$
using $b\ c\ d\ e\ TensorDiag-in-Hom\ red2-in-Hom\ TensorDiag-preserves-Ide$
 $TensorDiag-preserves-Diag\ assoc-naturality\ [of\ \{\{d\}\}\ \{\{e \Downarrow b\}\}\ \{\{c\}\}]$
 $comp-permute\ [of\ a[\{\{d\}\}, \{\{e \lfloor \otimes \rfloor b\}\}, \{\{c\}\}]\ (\{\{d\} \otimes \{\{e \Downarrow b\}\}\} \otimes \{\{c\}\})$
 $\{\{d\}\} \otimes (\{\{e \Downarrow b\}\} \otimes \{\{c\}\})\ a[\{\{d\}\}, \{\{e\} \otimes \{\{b\}\}, \{\{c\}\}]$
by *simp*
also have $\dots = (\{\{d\} \otimes \{\{e \lfloor \otimes \rfloor b\} \Downarrow c\}\}) \cdot (\{\{e \Downarrow b\} \otimes \{\{c\}\}\}) \cdot$
 $a[\{\{d\}\}, \{\{e\} \otimes \{\{b\}\}, \{\{c\}\}] \cdot (a[\{\{d\}\}, \{\{e\}\}, \{\{b\}\}] \otimes \{\{c\}\})$
using $b\ c\ d\ e\ TensorDiag-in-Hom\ red2-in-Hom\ TensorDiag-preserves-Ide$
 $TensorDiag-preserves-Diag\ interchange$
 $comp-reduce\ [of\ \{\{d\}\} \otimes \{\{e \lfloor \otimes \rfloor b\} \Downarrow c\}]$
 $\{\{d\}\} \otimes (\{\{e \Downarrow b\}\} \otimes \{\{c\}\})$

$$\{d\} \otimes \{(e \lfloor \otimes \rfloor b) \Downarrow c\} \cdot (\{e \Downarrow b\} \otimes \{c\})$$

$$a[\{d\}, \{e\} \otimes \{b\}, \{c\}] \cdot (a[\{d\}, \{e\}, \{b\}] \otimes \{c\})$$

by *simp*

also have ... = $((\{d\} \otimes \{e \Downarrow (b \lfloor \otimes \rfloor c)\}) \cdot (\{d\} \otimes \{e\} \otimes \{b \Downarrow c\})) \cdot$
 $(\{d\} \otimes a[\{e\}, \{b\}, \{c\}]) \cdot$
 $a[\{d\}, \{e\} \otimes \{b\}, \{c\}] \cdot (a[\{d\}, \{e\}, \{b\}] \otimes \{c\})$

using *b c d e I TensorDiag-in-Hom red2-in-Hom TensorDiag-preserves-Ide*
TensorDiag-preserves-Diag interchange

by *simp*

also have ... = $((\{d\} \otimes \{e \Downarrow (b \lfloor \otimes \rfloor c)\}) \cdot (\{d\} \otimes (\{e\} \otimes \{b \Downarrow c\}))) \cdot$
 $a[\{d\}, \{e\}, \{b\} \otimes \{c\}] \cdot a[\{d\} \otimes \{e\}, \{b\}, \{c\}]$

using *b c d e comp-assoc red2-in-Hom TensorDiag-in-Hom ide-eval-Ide*
TensorDiag-preserves-Diag tensor-preserves-ide TensorDiag-preserves-Ide
pentagon

by *simp*

The pentagon is used!

also have ... = $((\{d\} \otimes \{e \lfloor \otimes \rfloor b \lfloor \otimes \rfloor c\}) \cdot (\{d\} \otimes \{e \Downarrow b \lfloor \otimes \rfloor c\})) \cdot$
 $a[\{d\}, \{e\}, \{b \lfloor \otimes \rfloor c\}] \cdot ((\{d\} \otimes \{e\}) \otimes \{b \Downarrow c\}) \cdot$
 $a[\{d\} \otimes \{e\}, \{b\}, \{c\}]$

using *b c d e red2-in-Hom TensorDiag-preserves-Ide TensorDiag-preserves-Diag*
assoc-naturality [of \{d\} \{e\} \{b \Downarrow c\}] comp-cod-arr comp-assoc

by *simp*

also have ... = $(\{d \otimes e\} \Downarrow (b \lfloor \otimes \rfloor c)) \cdot ((\{d\} \otimes \{e\}) \otimes \{b \Downarrow c\}) \cdot$
 $a[\{d\} \otimes \{e\}, \{b\}, \{c\}]$

proof –

have $(d \otimes e) \Downarrow (b \lfloor \otimes \rfloor c)$
 $= (\{d\} \otimes \{e \lfloor \otimes \rfloor (b \lfloor \otimes \rfloor c)\}) \cdot (\{d\} \otimes \{e \Downarrow (b \lfloor \otimes \rfloor c)\}) \cdot$
 $a[\{d\}, \{e\}, \{b \lfloor \otimes \rfloor c\}]$

proof –

have $(d \otimes e) \Downarrow (b \lfloor \otimes \rfloor c)$
 $= (d \Downarrow (e \lfloor \otimes \rfloor [b \lfloor \otimes \rfloor c])) \cdot (d \otimes (e \Downarrow (b \lfloor \otimes \rfloor c))) \cdot a[d, e, b \lfloor \otimes \rfloor c]$

using *b c e not-is-Tensor-TensorDiagE*

by (*cases b \lfloor \otimes \rfloor c*) *auto*

also have ... = $(d \Downarrow (e \lfloor \otimes \rfloor (b \lfloor \otimes \rfloor c))) \cdot (d \otimes (e \Downarrow (b \lfloor \otimes \rfloor c))) \cdot$
 $a[d, e, b \lfloor \otimes \rfloor c]$

using *b c d e 1 TensorDiag-preserves-Diag Diagonalize-Diag* by *simp*

also have ... = $(d \otimes (e \lfloor \otimes \rfloor (b \lfloor \otimes \rfloor c))) \cdot (d \otimes (e \Downarrow (b \lfloor \otimes \rfloor c))) \cdot$
 $a[d, e, b \lfloor \otimes \rfloor c]$

using *b c d e 1 TensorDiag-preserves-Diag(1) red2-Diag*
by (*metis Diag.simps(3) de not-is-Tensor-Unity*)

finally have $(d \otimes e) \Downarrow (b \lfloor \otimes \rfloor c)$
 $= (d \otimes (e \lfloor \otimes \rfloor (b \lfloor \otimes \rfloor c))) \cdot (d \otimes (e \Downarrow (b \lfloor \otimes \rfloor c))) \cdot$
 $a[d, e, b \lfloor \otimes \rfloor c]$

by *blast*

thus *?thesis*

using *b c d e red2-in-Hom TensorDiag-in-Hom TensorDiag-preserves-Diag*
TensorDiag-preserves-Ide

by *simp*

qed
 thus ?thesis using d e b c by simp
 qed
 finally show ?thesis by simp
 qed
 qed
 qed
 thus ?thesis using assms(1) by blast
 qed
 ultimately show ?thesis by blast
 qed

lemma coherent-Assoc-Ide:

assumes Ide a and Ide b and Ide c

shows coherent a[a, b, c]

proof –

have a: Ide a \wedge Arr a \wedge Dom a = a \wedge Cod a = a \wedge
 ide $\{a\} \wedge$ ide $\{[a]\} \wedge$ « $\{a\downarrow\} : \{a\} \rightarrow \{[a]\}$ »
 using assms Ide-implies-Arr Ide-in-Hom Diagonalize-preserves-Ide red-in-Hom by auto
 have b: Ide b \wedge Arr b \wedge Dom b = b \wedge Cod b = b \wedge
 ide $\{b\} \wedge$ ide $\{[b]\} \wedge$ « $\{b\downarrow\} : \{b\} \rightarrow \{[b]\}$ »
 using assms Ide-implies-Arr Ide-in-Hom Diagonalize-preserves-Ide red-in-Hom by auto
 have c: Ide c \wedge Arr c \wedge Dom c = c \wedge Cod c = c \wedge
 ide $\{c\} \wedge$ ide $\{[c]\} \wedge$ « $\{c\downarrow\} : \{c\} \rightarrow \{[c]\}$ »
 using assms Ide-implies-Arr Ide-in-Hom Diagonalize-preserves-Ide red-in-Hom by auto
 have $\{Cod\ a[a, b, c]\downarrow\} \cdot \{a[a, b, c]\}$
 = ($\{[a] \downarrow ([b] [\otimes] [c])\} \cdot (\{[a]\} \otimes (\{[b] \downarrow [c]\})$) \cdot
 ($\{a\downarrow\} \otimes \{b\downarrow\} \otimes \{c\downarrow\}$)) \cdot a[$\{a\}, \{b\}, \{c\}$]
 using a b c red-in-Hom red2-in-Hom Diagonalize-in-Hom Diag-Diagonalize
 Diagonalize-preserves-Ide interchange Ide-in-Hom eval-red-Tensor
 comp-cod-arr [of $\{a\downarrow\}$]
 by simp
 also have ... = (($\{[a] \downarrow ([b] [\otimes] [c])\} \cdot (\{[a]\} \otimes \{[b] \downarrow [c]\})$) \cdot
 a[$\{[a]\}, \{[b]\}, \{[c]\}$]) \cdot (($\{a\downarrow\} \otimes \{b\downarrow\} \otimes \{c\downarrow\}$)
 using a b c red-in-Hom Diag-Diagonalize TensorDiag-preserves-Diag
 assoc-naturality [of $\{a\downarrow\} \{b\downarrow\} \{c\downarrow\}$] comp-assoc
 by simp
 also have ... = (($\{([a] [\otimes] [b]) \downarrow [c]\} \cdot (\{[a] \downarrow [b]\} \otimes \{[c]\})$) \cdot
 (($\{a\downarrow\} \otimes \{b\downarrow\} \otimes \{c\downarrow\}$))
 using a b c Diag-Diagonalize Diagonalize-preserves-Ide coherence-key-fact by simp
 also have ... = $\{[a[a, b, c]]\} \cdot \{Dom\ a[a, b, c]\downarrow\}$
 using a b c red-in-Hom red2-in-Hom TensorDiag-preserves-Diag
 Diagonalize-preserves-Ide TensorDiag-preserves-Ide Diag-Diagonalize interchange
 eval-red-Tensor TensorDiag-assoc comp-cod-arr [of $\{c\downarrow\}$]
 comp-cod-arr [of $\{([a] [\otimes] [b]) \downarrow [c]\} \cdot (\{[a] \downarrow [b]\} \cdot (\{a\downarrow\} \otimes \{b\downarrow\} \otimes \{c\downarrow\})$)]
 comp-assoc
 by simp
 finally show ?thesis by blast
 qed

lemma *coherent-Assoc'-Ide*:
assumes *Ide a and Ide b and Ide c*
shows *coherent a⁻¹[a, b, c]*
proof –
 have *Can a[a, b, c]* **using** *assms Ide-implies-Can by simp*
 moreover have *a⁻¹[a, b, c] = Inv a[a, b, c]*
 using *assms Inv-Ide by simp*
 ultimately show *?thesis*
 using *assms Ide-implies-Can coherent-Assoc-Ide Inv-Ide*
 Can-implies-coherent-iff-coherent-Inv
 by *metis*
qed

The next lemma implies coherence for the special case of a term that is the tensor of two diagonal arrows.

lemma *eval-red2-naturality*:
assumes *Diag t and Diag u*
shows $\{\{Cod\ t \Downarrow Cod\ u\} \cdot (\{\{t\} \otimes \{u\}\}) = \{\{t\} [\otimes] u\} \cdot \{\{Dom\ t \Downarrow Dom\ u\}\}$
proof –
 have $*$: $\bigwedge t\ u. Diag\ (t \otimes u) \implies arr\ \{\{t\}\} \wedge arr\ \{\{u\}\}$
 using *Diag-implies-Arr by force*
 have $t = \mathcal{I} \implies ?thesis$
 using *assms Diag-implies-Arr lunit-naturality [of \{u\}]*
 Arr-implies-Ide-Dom Arr-implies-Ide-Cod comp-cod-arr
 by *simp*
 moreover have $t \neq \mathcal{I} \wedge u = \mathcal{I} \implies ?thesis$
 using *assms Arr-implies-Ide-Dom Arr-implies-Ide-Cod*
 Diag-implies-Arr Dom-preserves-Diag Cod-preserves-Diag
 eval-red2-Diag-Unity runit-naturality [of \{t\}]
 by *simp*
 moreover have $t \neq \mathcal{I} \wedge u \neq \mathcal{I} \implies ?thesis$
 using $*$ *Arr-implies-Ide-Dom Arr-implies-Ide-Cod*
 Diag-implies-Arr Dom-preserves-Diag Cod-preserves-Diag
 apply (*induct t, simp-all*)
proof –
 fix f
 assume $f: C.arr\ f$
 assume $u \neq \mathcal{I}$
 hence $u: u \neq \mathcal{I} \wedge$
 $Diag\ u \wedge Diag\ (Dom\ u) \wedge Diag\ (Cod\ u) \wedge Ide\ (Dom\ u) \wedge Ide\ (Cod\ u) \wedge$
 $arr\ \{\{u\}\} \wedge arr\ \{\{Dom\ u\}\} \wedge arr\ \{\{Cod\ u\}\} \wedge ide\ \{\{Dom\ u\}\} \wedge ide\ \{\{Cod\ u\}\}$
 using *assms(2) Diag-implies-Arr Dom-preserves-Diag Cod-preserves-Diag*
 Arr-implies-Ide-Dom Arr-implies-Ide-Cod
 by *simp*
 hence $1: Dom\ u \neq \mathcal{I} \wedge Cod\ u \neq \mathcal{I}$ **using** u **by** (*cases u, simp-all*)
 show $\{\{C.cod\ f\} \Downarrow Cod\ u\} \cdot (Vf \otimes \{\{u\}\}) = (Vf \otimes \{\{u\}\}) \cdot \{\{C.dom\ f\} \Downarrow Dom\ u\}$
 using $f\ u\ 1$ *Diag-implies-Arr red2-Diag comp-arr-dom comp-cod-arr by simp*
next

fix $v\ w$
assume $I2: \llbracket w \neq \text{Unity}; \text{Diag } w \rrbracket \implies$
 $\{\!\{ \text{Cod } w \downarrow \text{Cod } u \}\!\} \cdot (\{\!\{ w \}\!\} \otimes \{\!\{ u \}\!\}) = \{\!\{ w \llbracket \otimes \rrbracket u \}\!\} \cdot \{\!\{ \text{Dom } w \downarrow \text{Dom } u \}\!\}$
assume $u \neq \mathcal{I}$
hence $u: u \neq \mathcal{I} \wedge \text{Arr } u \wedge \text{Arr } (\text{Dom } u) \wedge \text{Arr } (\text{Cod } u) \wedge$
 $\text{Diag } u \wedge \text{Diag } (\text{Dom } u) \wedge \text{Diag } (\text{Cod } u) \wedge \text{Ide } (\text{Dom } u) \wedge \text{Ide } (\text{Cod } u) \wedge$
 $\text{arr } \{\!\{ u \}\!\} \wedge \text{arr } \{\!\{ \text{Dom } u \}\!\} \wedge \text{arr } \{\!\{ \text{Cod } u \}\!\} \wedge \text{ide } \{\!\{ \text{Dom } u \}\!\} \wedge \text{ide } \{\!\{ \text{Cod } u \}\!\}$
using $\text{assms}(2)$ $\text{Diag-implies-Arr Dom-preserves-Diag Cod-preserves-Diag}$
 $\text{Arr-implies-Ide-Dom Arr-implies-Ide-Cod}$
by simp
assume $vw: \text{Diag } (v \otimes w)$
let $?f = \text{un-Prim } v$
have $v = \langle ?f \rangle \wedge C.\text{arr } ?f$
using vw **by** $(\text{metis } \text{Diag-TensorE}(1) \text{Diag-TensorE}(2))$
hence $\text{Arr } v \wedge v = \langle \text{un-Prim } v \rangle \wedge C.\text{arr } ?f \wedge \text{Diag } v$ **by** $(\text{cases } v; \text{simp})$
hence $v: v = \langle ?f \rangle \wedge C.\text{arr } ?f \wedge \text{Arr } v \wedge \text{Ide } (\text{Dom } v) \wedge \text{Ide } (\text{Cod } v) \wedge \text{Diag } v \wedge$
 $\text{Diag } (\text{Dom } v) \wedge \text{arr } \{\!\{ v \}\!\} \wedge \text{arr } \{\!\{ \text{Dom } v \}\!\} \wedge \text{arr } \{\!\{ \text{Cod } v \}\!\} \wedge$
 $\text{ide } \{\!\{ \text{Dom } v \}\!\} \wedge \text{ide } \{\!\{ \text{Cod } v \}\!\}$
by $(\text{cases } v, \text{simp-all})$
have $\text{Diag } w \wedge w \neq \mathcal{I}$
using $vw\ v$ **by** $(\text{metis } \text{Diag.simps}(3))$
hence $w: w \neq \mathcal{I} \wedge \text{Arr } w \wedge \text{Arr } (\text{Dom } w) \wedge \text{Arr } (\text{Cod } w) \wedge$
 $\text{Diag } w \wedge \text{Diag } (\text{Dom } w) \wedge \text{Diag } (\text{Cod } w) \wedge$
 $\text{Ide } (\text{Dom } w) \wedge \text{Ide } (\text{Cod } w) \wedge$
 $\text{arr } \{\!\{ w \}\!\} \wedge \text{arr } \{\!\{ \text{Dom } w \}\!\} \wedge \text{arr } \{\!\{ \text{Cod } w \}\!\} \wedge \text{ide } \{\!\{ \text{Dom } w \}\!\} \wedge \text{ide } \{\!\{ \text{Cod } w \}\!\}$
using $vw * \text{Diag-implies-Arr Dom-preserves-Diag Cod-preserves-Diag Arr-implies-Ide-Dom}$
 $\text{Arr-implies-Ide-Cod ide-eval-Ide Ide-implies-Arr Ide-in-Hom}$
by simp
show $\{\!\{ (\text{Cod } v \otimes \text{Cod } w) \downarrow \text{Cod } u \}\!\} \cdot (\{\!\{ v \}\!\} \otimes \{\!\{ w \}\!\}) \otimes \{\!\{ u \}\!\}$
 $= \{\!\{ (v \otimes w) \llbracket \otimes \rrbracket u \}\!\} \cdot \{\!\{ (\text{Dom } v \otimes \text{Dom } w) \downarrow \text{Dom } u \}\!\}$
proof –
have $u': \text{Dom } u \neq \mathcal{I} \wedge \text{Cod } u \neq \mathcal{I}$ **using** u **by** $(\text{cases } u) \text{simp-all}$
have $w': \text{Dom } w \neq \mathcal{I} \wedge \text{Cod } w \neq \mathcal{I}$ **using** w **by** $(\text{cases } w) \text{simp-all}$
have $D: \text{Diag } (\text{Dom } v \otimes (\text{Dom } w \llbracket \otimes \rrbracket \text{Dom } u))$
proof –
have $\text{Dom } w \llbracket \otimes \rrbracket \text{Dom } u \neq \mathcal{I}$
using $u\ u'\ w\ w'$ $\text{not-is-Tensor-TensorDiagE}$ **by** blast
moreover **have** $\text{Diag } (\text{Dom } w \llbracket \otimes \rrbracket \text{Dom } u)$
using $u\ w$ $\text{TensorDiag-preserves-Diag}$ **by** simp
moreover **have** $\text{Dom } v = \langle C.\text{dom } ?f \rangle$
using v **by** $(\text{cases } v, \text{simp-all})$
ultimately **show** $?thesis$
using $u\ v\ w$ $\text{TensorDiag-preserves-Diag}$ **by** auto
qed
have $C: \text{Diag } (\text{Cod } v \otimes (\text{Cod } w \llbracket \otimes \rrbracket \text{Cod } u))$
proof –
have $\text{Cod } w \llbracket \otimes \rrbracket \text{Cod } u \neq \mathcal{I}$
using $u\ u'\ w\ w'$ $\text{not-is-Tensor-TensorDiagE}$ **by** blast
moreover **have** $\text{Diag } (\text{Cod } w \llbracket \otimes \rrbracket \text{Cod } u)$

using $u\ w\ \text{TensorDiag-preserves-Diag}$ **by** simp
moreover have $\text{Cod } v = \langle C.\text{cod } ?f \rangle$
using v **by** $(\text{cases } v, \text{simp-all})$
ultimately show $?thesis$
using $u\ v\ w$ **by** $(\text{cases } \text{Cod } w\ [\otimes]\ \text{Cod } u)\ \text{simp-all}$
qed
have $\{(\text{Cod } v \otimes \text{Cod } w) \Downarrow \text{Cod } u\} \cdot ((\{v\} \otimes \{w\}) \otimes \{u\})$
 $= (\{ \text{Cod } v \Downarrow (\text{Cod } w\ [\otimes]\ \text{Cod } u) \} \cdot (\{ \text{Cod } v \} \otimes \{ \text{Cod } w \Downarrow \text{Cod } u \})) \cdot$
 $\text{a}[\{ \text{Cod } v \}, \{ \text{Cod } w \}, \{ \text{Cod } u \}] \cdot ((\{v\} \otimes \{w\}) \otimes \{u\})$
proof –
have $(\text{Cod } v \otimes \text{Cod } w) \Downarrow \text{Cod } u$
 $= (\text{Cod } v \Downarrow (\text{Cod } w\ [\otimes]\ [\text{Cod } u])) \cdot (\text{Cod } v \otimes \text{Cod } w \Downarrow \text{Cod } u) \cdot$
 $\text{a}[\text{Cod } v, \text{Cod } w, \text{Cod } u]$
using $u\ v\ w$ **by** $(\text{cases } u, \text{simp-all})$
hence $\{(\text{Cod } v \otimes \text{Cod } w) \Downarrow \text{Cod } u\}$
 $= \{ \text{Cod } v \Downarrow (\text{Cod } w\ [\otimes]\ \text{Cod } u) \} \cdot (\{ \text{Cod } v \} \otimes \{ \text{Cod } w \Downarrow \text{Cod } u \}) \cdot$
 $\text{a}[\{ \text{Cod } v \}, \{ \text{Cod } w \}, \{ \text{Cod } u \}]$
using $u\ v\ w$ **by** simp
thus $?thesis$ **by** argo
qed
also have $\dots = ((\{ \text{Cod } v \} \otimes \{ \text{Cod } w\ [\otimes]\ \text{Cod } u \}) \cdot (\{ \text{Cod } v \} \otimes \{ \text{Cod } w \Downarrow \text{Cod } u \})) \cdot$
 $\text{a}[\{ \text{Cod } v \}, \{ \text{Cod } w \}, \{ \text{Cod } u \}] \cdot ((\{v\} \otimes \{w\}) \otimes \{u\})$
using $u\ v\ w\ C\ \text{red2-Diag}$ **by** simp
also have $\dots = ((\{ \text{Cod } v \} \otimes \{ \text{Cod } w \Downarrow \text{Cod } u \}) \cdot \text{a}[\{ \text{Cod } v \}, \{ \text{Cod } w \}, \{ \text{Cod } u \}]) \cdot$
 $((\{v\} \otimes \{w\}) \otimes \{u\})$
proof –
have $(\{ \text{Cod } v \} \otimes \{ \text{Cod } w\ [\otimes]\ \text{Cod } u \}) \cdot (\{ \text{Cod } v \} \otimes \{ \text{Cod } w \Downarrow \text{Cod } u \})$
 $= \{ \text{Cod } v \} \otimes \{ \text{Cod } w \Downarrow \text{Cod } u \}$
using $u\ v\ w\ \text{comp-cod-arr red2-in-Hom}$ **by** simp
moreover have
 $\text{seq}(\{ \text{Cod } v \} \otimes \{ \text{Cod } w\ [\otimes]\ \text{Cod } u \}) (\{ \text{Cod } v \} \otimes \{ \text{Cod } w \Downarrow \text{Cod } u \})$
using $u\ v\ w\ \text{red2-in-Hom TensorDiag-in-Hom Ide-in-Hom}$ **by** simp
moreover have $\text{seq}(\{ \text{Cod } v \} \otimes \{ \text{Cod } w \Downarrow \text{Cod } u \}) \text{a}[\{ \text{Cod } v \}, \{ \text{Cod } w \}, \{ \text{Cod } u \}]$
using $u\ v\ w\ \text{red2-in-Hom}$ **by** simp
ultimately show $?thesis$
using $u\ v\ w\ \text{comp-reduce}$ **by** presburger
qed
also have
 $\dots = (\{v\} \otimes \{w\ [\otimes]\ u\}) \cdot \{ \text{Dom } w \Downarrow \text{Dom } u \} \cdot \text{a}[\{ \text{Dom } v \}, \{ \text{Dom } w \}, \{ \text{Dom } u \}]$
using $u\ v\ w\ I2\ \text{red2-in-Hom TensorDiag-in-Hom interchange comp-reduce}$
 $\text{assoc-naturality [of } \{v\} \{w\} \{u\}] \text{comp-cod-arr comp-assoc}$
by simp
also have $\dots = (\{v\} \otimes \{w\ [\otimes]\ u\}) \cdot (\{ \text{Dom } v \} \otimes \{ \text{Dom } w \Downarrow \text{Dom } u \}) \cdot$
 $\text{a}[\{ \text{Dom } v \}, \{ \text{Dom } w \}, \{ \text{Dom } u \}]$
using $u\ v\ w\ \text{red2-in-Hom TensorDiag-in-Hom interchange comp-reduce comp-arr-dom}$
by simp
also have $\dots = \{v\ [\otimes]\ w\ [\otimes]\ u\} \cdot (\{ \text{Dom } v \} \otimes \{ \text{Dom } w \Downarrow \text{Dom } u \}) \cdot$
 $\text{a}[\{ \text{Dom } v \}, \{ \text{Dom } w \}, \{ \text{Dom } u \}]$
using $u\ u'\ v\ w\ \text{not-is-Tensor-TensorDiagE TensorDiag-Prim [of } w\ [\otimes]\ u\ ?f]$

by force
also have ... = $\{\!|v \lfloor \otimes \rfloor w \lfloor \otimes \rfloor u\!\} \cdot \{\!|Dom v \lfloor \otimes \rfloor Dom w \lfloor \otimes \rfloor Dom u\!\} \cdot$
 $(\{\!|Dom v\!\} \otimes \{\!|Dom w \Downarrow Dom u\!\}) \cdot a[\{\!|Dom v\!\}, \{\!|Dom w\!\}, \{\!|Dom u\!\}]$
proof –
have
 $\{\!|v \lfloor \otimes \rfloor w \lfloor \otimes \rfloor u\!\} \cdot (\{\!|Dom v\!\} \otimes \{\!|Dom w \Downarrow Dom u\!\}) \cdot$
 $a[\{\!|Dom v\!\}, \{\!|Dom w\!\}, \{\!|Dom u\!\}] =$
 $(\{\!|v \lfloor \otimes \rfloor w \lfloor \otimes \rfloor u\!\} \cdot \{\!|Dom v \lfloor \otimes \rfloor Dom w \lfloor \otimes \rfloor Dom u\!\}) \cdot$
 $(\{\!|Dom v\!\} \otimes \{\!|Dom w \Downarrow Dom u\!\}) \cdot a[\{\!|Dom v\!\}, \{\!|Dom w\!\}, \{\!|Dom u\!\}]$
using *u v w comp-arr-dom TensorDiag-in-Hom TensorDiag-preserves-Diag* **by simp**
also have ... = $\{\!|v \lfloor \otimes \rfloor w \lfloor \otimes \rfloor u\!\} \cdot \{\!|Dom v \lfloor \otimes \rfloor Dom w \lfloor \otimes \rfloor Dom u\!\} \cdot$
 $(\{\!|Dom v\!\} \otimes \{\!|Dom w \Downarrow Dom u\!\}) \cdot a[\{\!|Dom v\!\}, \{\!|Dom w\!\}, \{\!|Dom u\!\}]$
using *comp-assoc* **by simp**
finally show *?thesis* **by blast**
qed
also have ... = $\{\!|(v \lfloor \otimes \rfloor w) \lfloor \otimes \rfloor u\!\} \cdot \{\!|(Dom v \otimes Dom w) \Downarrow Dom u\!\}$
proof –
have
 $\{\!|(Dom v \otimes Dom w) \Downarrow Dom u\!\}$
 $= \{\!|Dom v \Downarrow (Dom w \lfloor \otimes \rfloor Dom u)\!\} \cdot (\{\!|Dom v\!\} \otimes \{\!|Dom w \Downarrow Dom u\!\}) \cdot$
 $a[\{\!|Dom v\!\}, \{\!|Dom w\!\}, \{\!|Dom u\!\}]$
proof –
have $(Dom v \otimes Dom w) \Downarrow Dom u$
 $= (Dom v \Downarrow (Dom w \lfloor \otimes \rfloor \lfloor Dom u \rfloor)) \cdot (Dom v \otimes (Dom w \Downarrow Dom u)) \cdot$
 $a[Dom v, Dom w, Dom u]$
using *u u' v w red2-in-Hom TensorDiag-in-Hom Ide-in-Hom*
by *(cases u) auto*
thus *?thesis*
using *u v w red2-in-Hom* **by simp**
qed
also have
... = $\{\!|Dom v \lfloor \otimes \rfloor Dom w \lfloor \otimes \rfloor Dom u\!\} \cdot (\{\!|Dom v\!\} \otimes \{\!|Dom w \Downarrow Dom u\!\}) \cdot$
 $a[\{\!|Dom v\!\}, \{\!|Dom w\!\}, \{\!|Dom u\!\}]$
using *D TensorDiag-Diag red2-Diag* **by simp**
finally have
 $\{\!|(Dom v \otimes Dom w) \Downarrow Dom u\!\}$
 $= \{\!|Dom v \lfloor \otimes \rfloor Dom w \lfloor \otimes \rfloor Dom u\!\} \cdot (\{\!|Dom v\!\} \otimes \{\!|Dom w \Downarrow Dom u\!\}) \cdot$
 $a[\{\!|Dom v\!\}, \{\!|Dom w\!\}, \{\!|Dom u\!\}]$
by blast
thus *?thesis*
using *assms v w TensorDiag-assoc* **by auto**
qed
finally show *?thesis*
using *vw TensorDiag-Diag* **by simp**
qed
qed
ultimately show *?thesis* **by blast**
qed

lemma *Tensor-preserves-coherent:*

assumes *Arr t and Arr u and coherent t and coherent u*

shows *coherent (t ⊗ u)*

proof –

have $t: \text{Arr } t \wedge \text{Ide } (\text{Dom } t) \wedge \text{Ide } (\text{Cod } t) \wedge \text{Ide } \lfloor \text{Dom } t \rfloor \wedge \text{Ide } \lfloor \text{Cod } t \rfloor \wedge$
 $\text{arr } \{t\} \wedge \text{arr } \{ \text{Dom } t \} \wedge \text{ide } \{ \text{Dom } t \} \wedge \text{arr } \{ \text{Cod } t \} \wedge \text{ide } \{ \text{Cod } t \}$
using *assms Arr-implies-Ide-Dom Arr-implies-Ide-Cod Diagonalize-preserves-Ide*
by *auto*

have $u: \text{Arr } u \wedge \text{Ide } (\text{Dom } u) \wedge \text{Ide } (\text{Cod } u) \wedge \text{Ide } \lfloor \text{Dom } u \rfloor \wedge \text{Ide } \lfloor \text{Cod } u \rfloor \wedge$
 $\text{arr } \{u\} \wedge \text{arr } \{ \text{Dom } u \} \wedge \text{ide } \{ \text{Dom } u \} \wedge \text{arr } \{ \text{Cod } u \} \wedge \text{ide } \{ \text{Cod } u \}$
using *assms Arr-implies-Ide-Dom Arr-implies-Ide-Cod Diagonalize-preserves-Ide*
by *auto*

have $\{ \text{Cod } (t \otimes u) \downarrow \} \cdot (\{t\} \otimes \{u\})$
 $= (\{ \lfloor \text{Cod } t \rfloor \downarrow \lfloor \text{Cod } u \rfloor \} \cdot (\{ \text{Cod } t \downarrow \} \otimes \{ \text{Cod } u \downarrow \})) \cdot (\{t\} \otimes \{u\})$

using *t u eval-red-Tensor by simp*

also have $\dots = \{ \lfloor \text{Cod } t \rfloor \downarrow \lfloor \text{Cod } u \rfloor \} \cdot (\{ \text{Cod } t \downarrow \} \otimes \{ \text{Cod } u \downarrow \}) \cdot (\{t\} \otimes \{u\})$

using *comp-assoc by simp*

also have $\dots = \{ \lfloor \text{Cod } t \rfloor \downarrow \lfloor \text{Cod } u \rfloor \} \cdot (\{ \lfloor t \rfloor \} \otimes \{ \lfloor u \rfloor \}) \cdot (\{ \text{Dom } t \downarrow \} \otimes \{ \text{Dom } u \downarrow \})$

using *assms t u Diagonalize-in-Hom red-in-Hom interchange by simp*

also have $\dots = (\{ \lfloor \text{Cod } t \rfloor \downarrow \lfloor \text{Cod } u \rfloor \} \cdot (\{ \lfloor t \rfloor \} \otimes \{ \lfloor u \rfloor \})) \cdot (\{ \text{Dom } t \downarrow \} \otimes \{ \text{Dom } u \downarrow \})$

using *comp-assoc by simp*

also have $\dots = (\{ \lfloor t \rfloor \lfloor \otimes \rfloor \lfloor u \rfloor \} \cdot \{ \lfloor \text{Dom } t \rfloor \downarrow \lfloor \text{Dom } u \rfloor \}) \cdot (\{ \text{Dom } t \downarrow \} \otimes \{ \text{Dom } u \downarrow \})$

using *assms t u Diag-Diagonalize Diagonalize-in-Hom*

eval-red2-naturality [of Diagonalize t Diagonalize u]

by *simp*

also have $\dots = \{ \lfloor t \rfloor \lfloor \otimes \rfloor \lfloor u \rfloor \} \cdot \{ \lfloor \text{Dom } t \rfloor \downarrow \lfloor \text{Dom } u \rfloor \} \cdot (\{ \text{Dom } t \downarrow \} \otimes \{ \text{Dom } u \downarrow \})$

using *comp-assoc by simp*

also have $\dots = \{ \lfloor t \rfloor \lfloor \otimes \rfloor \lfloor u \rfloor \} \cdot \{ (\text{Dom } t \otimes \text{Dom } u) \downarrow \}$

using *t u eval-red-Tensor by simp*

finally have $\{ \text{Cod } (t \otimes u) \downarrow \} \cdot (\{t\} \otimes \{u\}) = \{ \lfloor t \rfloor \lfloor \otimes \rfloor \lfloor u \rfloor \} \cdot \{ (\text{Dom } t \otimes \text{Dom } u) \downarrow \}$
by *blast*

thus *?thesis using t u by simp*

qed

lemma *Comp-preserves-coherent:*

assumes *Arr t and Arr u and Dom t = Cod u*

and *coherent t and coherent u*

shows *coherent (t · u)*

proof –

have $t: \text{Arr } t \wedge \text{Ide } (\text{Dom } t) \wedge \text{Ide } (\text{Cod } t) \wedge \text{Ide } \lfloor \text{Dom } t \rfloor \wedge \text{Ide } \lfloor \text{Cod } t \rfloor \wedge$
 $\text{arr } \{t\} \wedge \text{arr } \{ \text{Dom } t \} \wedge \text{ide } \{ \text{Dom } t \} \wedge \text{arr } \{ \text{Cod } t \} \wedge \text{ide } \{ \text{Cod } t \}$
using *assms Arr-implies-Ide-Dom Arr-implies-Ide-Cod Diagonalize-preserves-Ide*
by *auto*

have $u: \text{Arr } u \wedge \text{Ide } (\text{Dom } u) \wedge \text{Ide } (\text{Cod } u) \wedge \text{Ide } \lfloor \text{Dom } u \rfloor \wedge \text{Ide } \lfloor \text{Cod } u \rfloor \wedge$
 $\text{arr } \{u\} \wedge \text{arr } \{ \text{Dom } u \} \wedge \text{ide } \{ \text{Dom } u \} \wedge \text{arr } \{ \text{Cod } u \} \wedge \text{ide } \{ \text{Cod } u \}$
using *assms Arr-implies-Ide-Dom Arr-implies-Ide-Cod Diagonalize-preserves-Ide*
by *auto*

have $\{ \text{Cod } (t \cdot u) \downarrow \} \cdot \{t \cdot u\} = \{ \text{Cod } t \downarrow \} \cdot \{t\} \cdot \{u\}$

using *t u by simp*

```

also have ... = ( $\{Cod\ t\downarrow\} \cdot \{t\}$ )  $\cdot$   $\{u\}$ 
proof -

  have seq  $\{Cod\ t\downarrow\} \{t\}$ 
    using assms t red-in-Hom by (intro seqI, auto)
  moreover have seq  $\{t\} \{u\}$ 
    using assms t u by auto
  ultimately show ?thesis using comp-assoc by auto
qed
also have ... =  $\{[t \cdot u]\} \cdot \{Dom\ (t \cdot u)\downarrow\}$ 
  using t u assms red-in-Hom Diag-Diagonalize comp-assoc
  by (simp add: Diag-implies-Arr eval-CompDiag)
finally show coherent (t · u) by blast
qed

```

The main result: “Every formal arrow is coherent.”

theorem *coherence*:

assumes *Arr t*

shows *coherent t*

proof –

have *Arr t* \implies *coherent t*

proof (*induct t*)

fix *u v*

show $\llbracket Arr\ u \implies\ coherent\ u;\ Arr\ v \implies\ coherent\ v \rrbracket \implies Arr\ (u \otimes v)$
 $\implies coherent\ (u \otimes v)$

using *Tensor-preserves-coherent* by *simp*

show $\llbracket Arr\ u \implies\ coherent\ u;\ Arr\ v \implies\ coherent\ v \rrbracket \implies Arr\ (u \cdot v)$
 $\implies coherent\ (u \cdot v)$

using *Comp-preserves-coherent* by *simp*

next

show *coherent* \mathcal{I} by *simp*

fix *f*

show *Arr* $\langle f \rangle \implies coherent\ \langle f \rangle$ by *simp*

next

fix *t*

assume *I*: *Arr t* $\implies coherent\ t$

show *Lunit*: *Arr* $\mathbf{l}[t] \implies coherent\ \mathbf{l}[t]$

using *I Arr-implies-Ide-Dom coherent-Lunit-Ide Ide-in-Hom Ide-implies-Arr*
Comp-preserves-coherent [of t $\mathbf{l}[Dom\ t]$] Diagonalize-Comp-Arr-Dom \mathbf{l} -ide-simp
 by *auto*

show *Runit*: *Arr* $\mathbf{r}[t] \implies coherent\ \mathbf{r}[t]$

using *I Arr-implies-Ide-Dom coherent-Runit-Ide Ide-in-Hom Ide-implies-Arr*
Comp-preserves-coherent [of t $\mathbf{r}[Dom\ t]$] Diagonalize-Comp-Arr-Dom \mathbf{r} -ide-simp
 by *auto*

show *Arr* $\mathbf{l}^{-1}[t] \implies coherent\ \mathbf{l}^{-1}[t]$

proof –

assume *Arr* $\mathbf{l}^{-1}[t]$

hence *t*: *Arr t* by *simp*

have *coherent* $(\mathbf{l}^{-1}[Cod\ t] \cdot t)$


```

using  $t$  I Arr-implies-Ide-Cod coherent-Lunit'-Ide Ide-in-Hom
      Comp-preserves-coherent [of  $\mathbf{1}^{-1}[\text{Cod } t]$   $t$ ]
by fastforce
thus ?thesis
using  $t$  Arr-implies-Ide-Cod Ide-implies-Arr Ide-in-Hom Diagonalize-Comp-Cod-Arr
      eval-in-hom  $\mathbf{1}'$ .naturality2 [of  $\{\!|t|\}$ ]
by force
qed
show  $\text{Arr } \mathbf{r}^{-1}[t] \implies \text{coherent } \mathbf{r}^{-1}[t]$ 
proof –
  assume  $\text{Arr } \mathbf{r}^{-1}[t]$ 
  hence  $t: \text{Arr } t$  by simp
  have  $\text{coherent } (\mathbf{r}^{-1}[\text{Cod } t] \cdot t)$ 
    using  $t$  I Arr-implies-Ide-Cod coherent-Runit'-Ide Ide-in-Hom
      Comp-preserves-coherent [of  $\mathbf{r}^{-1}[\text{Cod } t]$   $t$ ]
    by fastforce
  thus ?thesis
  using  $t$  Arr-implies-Ide-Cod Ide-implies-Arr Ide-in-Hom Diagonalize-Comp-Cod-Arr
      eval-in-hom  $\rho'$ .naturality2 [of  $\{\!|t|\}$ ]
  by force
qed
next
fix  $t u v$ 
assume  $I1: \text{Arr } t \implies \text{coherent } t$ 
assume  $I2: \text{Arr } u \implies \text{coherent } u$ 
assume  $I3: \text{Arr } v \implies \text{coherent } v$ 
show  $\text{Arr } \mathbf{a}[t, u, v] \implies \text{coherent } \mathbf{a}[t, u, v]$ 
proof –
  assume  $tuv: \text{Arr } \mathbf{a}[t, u, v]$ 
  have  $t: \text{Arr } t$  using  $tuv$  by simp
  have  $u: \text{Arr } u$  using  $tuv$  by simp
  have  $v: \text{Arr } v$  using  $tuv$  by simp
  have  $\text{coherent } ((t \otimes u \otimes v) \cdot \mathbf{a}[\text{Dom } t, \text{Dom } u, \text{Dom } v])$ 
proof –
  have  $\text{Arr } (t \otimes u \otimes v) \wedge \text{coherent } (t \otimes u \otimes v)$ 
proof
  have  $1: \text{Arr } t \wedge \text{coherent } t$  using  $t$   $I1$  by simp
  have  $2: \text{Arr } (u \otimes v) \wedge \text{coherent } (u \otimes v)$ 
    using  $u v$   $I2$   $I3$  Tensor-preserves-coherent by force
  show  $\text{Arr } (t \otimes u \otimes v)$  using  $1$   $2$  by simp
  show  $\text{coherent } (t \otimes u \otimes v)$ 
    using  $1$   $2$  Tensor-preserves-coherent by blast
qed
moreover have  $\text{Arr } \mathbf{a}[\text{Dom } t, \text{Dom } u, \text{Dom } v]$ 
  using  $t u v$  Arr-implies-Ide-Dom by simp
moreover have  $\text{coherent } \mathbf{a}[\text{Dom } t, \text{Dom } u, \text{Dom } v]$ 
  using  $t u v$  Arr-implies-Ide-Dom coherent-Assoc-Ide by blast
moreover have  $\text{Dom } (t \otimes u \otimes v) = \text{Cod } \mathbf{a}[\text{Dom } t, \text{Dom } u, \text{Dom } v]$ 
  using  $t u v$  Arr-implies-Ide-Dom Ide-in-Hom by simp

```

ultimately show *?thesis*
using $t\ u\ v$ *Arr-implies-Ide-Dom Ide-implies-Arr*
Comp-preserves-coherent [of $t \otimes u \otimes v$ $\mathbf{a}[Dom\ t, Dom\ u, Dom\ v]$]
by *blast*
qed
moreover have $Par\ \mathbf{a}[t, u, v]\ ((t \otimes u \otimes v) \cdot \mathbf{a}[Dom\ t, Dom\ u, Dom\ v])$
using $t\ u\ v$ *Arr-implies-Ide-Dom Ide-implies-Arr Ide-in-Hom* **by** *simp*
moreover have $\lfloor \mathbf{a}[t, u, v] \rfloor = \lfloor (t \otimes u \otimes v) \cdot \mathbf{a}[Dom\ t, Dom\ u, Dom\ v] \rfloor$
proof –
have $(\lfloor t \rfloor \lfloor \otimes \rfloor \lfloor u \rfloor) \lfloor \otimes \rfloor \lfloor v \rfloor$
 $= (\lfloor t \rfloor \lfloor \otimes \rfloor \lfloor u \rfloor \lfloor \otimes \rfloor \lfloor v \rfloor) \lfloor \cdot \rfloor ((\lfloor Dom\ t \rfloor \lfloor \otimes \rfloor \lfloor Dom\ u \rfloor) \lfloor \otimes \rfloor \lfloor Dom\ v \rfloor)$
proof –
have $1: Diag\ \lfloor t \rfloor \wedge Diag\ \lfloor u \rfloor \wedge Diag\ \lfloor v \rfloor \wedge$
 $Dom\ \lfloor t \rfloor = \lfloor Dom\ t \rfloor \wedge Dom\ \lfloor u \rfloor = \lfloor Dom\ u \rfloor \wedge Dom\ \lfloor v \rfloor = \lfloor Dom\ v \rfloor$
using $t\ u\ v$ *Diag-Diagonalize* **by** *blast*
moreover have $Diag\ (\lfloor t \rfloor \lfloor \otimes \rfloor \lfloor u \rfloor)$
using 1 *TensorDiag-preserves-Diag(1)* **by** *blast*
moreover have $\wedge t. Arr\ t \implies \lfloor t \rfloor \lfloor \cdot \rfloor \lfloor Dom\ t \rfloor = \lfloor t \rfloor$
using t *Diagonalize-Comp-Arr-Dom* **by** *simp*
moreover have $Dom\ \lfloor \mathbf{a}[t, u, v] \rfloor = \lfloor Dom\ \mathbf{a}[t, u, v] \rfloor$
using *Diag-Diagonalize tuv* **by** *blast*
ultimately show *?thesis*
using $t\ u\ v\ tuv\ 1$ *TensorDiag-assoc TensorDiag-preserves-Diag(2)*
by *(metis (no-types) Diagonalize.simps(9))*
qed
thus *?thesis*
using $t\ u\ v$ *Diagonalize-Comp-Arr-Dom CompDiag-TensorDiag Diag-Diagonalize*
by *simp*
qed
moreover have $\{\mathbf{a}[t, u, v]\} = \{(t \otimes u \otimes v) \cdot \mathbf{a}[Dom\ t, Dom\ u, Dom\ v]\}$
using $t\ u\ v$ *Arr-implies-Ide-Dom Ide-implies-Arr α -simp* [of $\{t\}\ \{u\}\ \{v\}$]
by *simp*
ultimately show *coherent* $\mathbf{a}[t, u, v]$ **by** *argo*
qed
show $Arr\ \mathbf{a}^{-1}[t, u, v] \implies coherent\ \mathbf{a}^{-1}[t, u, v]$
proof –
assume $tuv: Arr\ \mathbf{a}^{-1}[t, u, v]$
have $t: Arr\ t$ **using** tuv **by** *simp*
have $u: Arr\ u$ **using** tuv **by** *simp*
have $v: Arr\ v$ **using** tuv **by** *simp*
have $coherent\ (((t \otimes u) \otimes v) \cdot \mathbf{a}^{-1}[Dom\ t, Dom\ u, Dom\ v])$
proof –
have $Arr\ ((t \otimes u) \otimes v) \wedge coherent\ ((t \otimes u) \otimes v)$
proof
have $1: Arr\ v \wedge coherent\ v$ **using** $v\ I3$ **by** *simp*
have $2: Arr\ (t \otimes u) \wedge coherent\ (t \otimes u)$
using $t\ u\ I1\ I2$ *Tensor-preserves-coherent* **by** *force*
show $Arr\ ((t \otimes u) \otimes v)$ **using** $1\ 2$ **by** *simp*
show $coherent\ ((t \otimes u) \otimes v)$

```

    using 1 2 Tensor-preserves-coherent by blast
  qed
  moreover have Arr a-1[Dom t, Dom u, Dom v]
    using t u v Arr-implies-Ide-Dom by simp
  moreover have coherent a-1[Dom t, Dom u, Dom v]
    using t u v Arr-implies-Ide-Dom coherent-Assoc'-Ide by blast
  moreover have Dom ((t ⊗ u) ⊗ v) = Cod a-1[Dom t, Dom u, Dom v]
    using t u v Arr-implies-Ide-Dom Ide-in-Hom by simp
  ultimately show ?thesis
    using t u v Arr-implies-Ide-Dom Ide-implies-Arr
      Comp-preserves-coherent [of ((t ⊗ u) ⊗ v) a-1[Dom t, Dom u, Dom v]]
    by metis
  qed
  moreover have Par a-1[t, u, v] (((t ⊗ u) ⊗ v) · a-1[Dom t, Dom u, Dom v])
    using t u v Arr-implies-Ide-Dom Ide-implies-Arr Ide-in-Hom by simp
  moreover have [a-1[t, u, v]] = [((t ⊗ u) ⊗ v) · a-1[Dom t, Dom u, Dom v]]
    using t u v Diagonalize-Comp-Arr-Dom CompDiag-TensorDiag Diag-Diagonalize
      TensorDiag-assoc TensorDiag-preserves-Diag TensorDiag-in-Hom
      CompDiag-Diag-Dom [of ([t] [⊗] [u]) [⊗] [v]]
    by simp
  moreover have {a-1[t, u, v]} = {((t ⊗ u) ⊗ v) · a-1[Dom t, Dom u, Dom v]}
    using t u v Arr-implies-Ide-Dom Ide-implies-Arr eval-in-hom comp-cod-arr
      α'.naturality1 α'-simp
    by simp
  ultimately show coherent a-1[t, u, v] by argo
  qed
  qed
  thus ?thesis using assms by blast
  qed

```

MacLane [5] says: “A coherence theorem asserts ‘Every diagram commutes,’” but that is somewhat misleading. A coherence theorem provides some kind of hopefully useful way of distinguishing diagrams that definitely commute from diagrams that might not. The next result expresses coherence for monoidal categories in this way. As the hypotheses can be verified algorithmically (using the functions *Dom*, *Cod*, *Arr*, and *Diagonalize*) if we are given an oracle for equality of arrows in *C*, the result provides a decision procedure, relative to *C*, for the word problem for the free monoidal category generated by *C*.

```

corollary eval-eqI:
assumes Par t u and [t] = [u]
shows {t} = {u}
  using assms coherence canonical-factorization by simp

```

Our final corollary expresses coherence in a more “MacLane-like” fashion: parallel canonical arrows are equivalent under evaluation.

```

corollary maclane-coherence:
assumes Par t u and Can t and Can u
shows {t} = {u}
proof (intro eval-eqI)
  show Par t u by fact

```

```

show [t] = [u]
proof -
  have Ide [t] ∧ Ide [u] ∧ Par [t] [u]
    using assms eval-eqI Ide-Diagonalize-Can Diagonalize-in-Hom by simp
  thus ?thesis using Ide-in-Hom by auto
qed
qed

end

end

```

Chapter 3

Monoidal Functor

```
theory MonoidalFunctor
imports MonoidalCategory
begin
```

A monoidal functor is a functor F between monoidal categories C and D that preserves the monoidal structure up to isomorphism. The traditional definition assumes a monoidal functor to be equipped with two natural isomorphisms, a natural isomorphism φ that expresses the preservation of tensor product and a natural isomorphism ψ that expresses the preservation of the unit object. These natural isomorphisms are subject to coherence conditions; the condition for φ involving the associator and the conditions for ψ involving the unitors. However, as pointed out in [2] (Section 2.4), it is not necessary to take the natural isomorphism ψ as given, since the mere assumption that $F \mathcal{I}_C$ is isomorphic to \mathcal{I}_D is sufficient for there to be a canonical definition of ψ from which the coherence conditions can be derived. This leads to a more economical definition of monoidal functor, which is the one we adopt here.

```
locale monoidal-functor =
  C: monoidal-category C T_C  $\alpha_C$   $\iota_C$  +
  D: monoidal-category D T_D  $\alpha_D$   $\iota_D$  +
  functor C D F +
  CC: product-category C C +
  DD: product-category D D +
  FF: product-functor C C D D F F +
  FoT_C: composite-functor C.CC.comp C D T_C F +
  T_D o FF: composite-functor C.CC.comp D.CC.comp D FF.map T_D +
   $\varphi$ : natural-isomorphism C.CC.comp D T_D o FF.map FoT_C.map  $\varphi$ 
for C :: 'c comp (infixr '<_C>' 55)
and T_C :: 'c * 'c  $\Rightarrow$  'c
and  $\alpha_C$  :: 'c * 'c * 'c  $\Rightarrow$  'c
and  $\iota_C$  :: 'c
and D :: 'd comp (infixr '<_D>' 55)
and T_D :: 'd * 'd  $\Rightarrow$  'd
and  $\alpha_D$  :: 'd * 'd * 'd  $\Rightarrow$  'd
and  $\iota_D$  :: 'd
```

and $F :: 'c \Rightarrow 'd$
and $\varphi :: 'c * 'c \Rightarrow 'd +$
assumes *preserves-unity*: $D.isomorphic\ D.unity\ (F\ C.unity)$
and *assoc-coherence*:

$$\llbracket C.ide\ a;\ C.ide\ b;\ C.ide\ c \rrbracket \Longrightarrow$$

$$F\ (\alpha_C\ (a,\ b,\ c)) \cdot_D\ \varphi\ (T_C\ (a,\ b),\ c) \cdot_D\ T_D\ (\varphi\ (a,\ b),\ F\ c)$$

$$= \varphi\ (a,\ T_C\ (b,\ c)) \cdot_D\ T_D\ (F\ a,\ \varphi\ (b,\ c)) \cdot_D\ \alpha_D\ (F\ a,\ F\ b,\ F\ c)$$
begin

notation $C.tensor$ **(infixr** $\langle \otimes_C \rangle$ 53)
and $C.unity$ $\langle \mathcal{I}_C \rangle$
and $C.lunit$ $\langle \mathcal{L}_C[-] \rangle$
and $C.runit$ $\langle \mathcal{R}_C[-] \rangle$
and $C.assoc$ $\langle \mathcal{a}_C[-,\ \cdot,\ -] \rangle$
and $D.tensor$ **(infixr** $\langle \otimes_D \rangle$ 53)
and $D.unity$ $\langle \mathcal{I}_D \rangle$
and $D.lunit$ $\langle \mathcal{L}_D[-] \rangle$
and $D.runit$ $\langle \mathcal{R}_D[-] \rangle$
and $D.assoc$ $\langle \mathcal{a}_D[-,\ \cdot,\ -] \rangle$

lemma φ -*in-hom*:
assumes $C.ide\ a$ **and** $C.ide\ b$
shows $\langle \varphi\ (a,\ b) : F\ a \otimes_D F\ b \rightarrow_D F\ (a \otimes_C b) \rangle$
using *assms by auto*

We wish to exhibit a canonical definition of an isomorphism $\psi \in D.hom\ \mathcal{I}_D\ (F\ \mathcal{I}_C)$ that satisfies certain coherence conditions that involve the left and right unitors. In [2], the isomorphism ψ is defined by the equation $\mathcal{L}_D[F\ \mathcal{I}_C] = F\ \mathcal{L}_C[\mathcal{I}_C] \cdot_D\ \varphi\ (\mathcal{I}_C,\ \mathcal{I}_C) \cdot_D\ (\psi \otimes_D F\ \mathcal{I}_C)$, which suffices for the definition because the functor $- \otimes_D F\ \mathcal{I}_C$ is fully faithful. It is then asserted (Proposition 2.4.3) that the coherence condition $\mathcal{L}_D[F\ a] = F\ \mathcal{L}_C[a] \cdot_D\ \varphi\ (\mathcal{I}_C,\ a) \cdot_D\ (\psi \otimes_D F\ a)$ is satisfied for any object a of C , as well as the corresponding condition for the right unitor. However, the proof is left as an exercise (Exercise 2.4.4). The organization of the presentation suggests that that one should derive the general coherence condition from the special case $\mathcal{L}_D[F\ \mathcal{I}_C] = F\ \mathcal{L}_C[\mathcal{I}_C] \cdot_D\ \varphi\ (\mathcal{I}_C,\ \mathcal{I}_C) \cdot_D\ (\psi \otimes_D F\ \mathcal{I}_C)$ used as the definition of ψ . However, I did not see how to do it that way, so I used a different approach. The isomorphism $\iota_D' \equiv F\ \iota_C \cdot_D\ \varphi\ (\mathcal{I}_C,\ \mathcal{I}_C)$ serves as an alternative unit for the monoidal category D . There is consequently a unique isomorphism that maps ι_D to ι_D' . We define ψ to be this isomorphism and then use the definition to establish the desired coherence conditions.

abbreviation ι_1
where $\iota_1 \equiv F\ \iota_C \cdot_D\ \varphi\ (\mathcal{I}_C,\ \mathcal{I}_C)$

lemma ι_1 -*in-hom*:
shows $\langle \iota_1 : F\ \mathcal{I}_C \otimes_D F\ \mathcal{I}_C \rightarrow_D F\ \mathcal{I}_C \rangle$
using $C.unit$ -*in-hom* **by** (*intro D.in-homI, auto*)

lemma ι_1 -*is-iso*:
shows $D.iso\ \iota_1$

using *C.unit-is-iso C.unit-in-hom φ -in-hom D.isos-compose* by *auto*

interpretation *D: monoidal-category-with-alternate-unit* $D T_D \alpha_D \iota_D \iota_1$

proof –

have *1*: $\exists \psi. \langle \psi : F \mathcal{I}_C \rightarrow_D \mathcal{I}_D \rangle \wedge D.iso \psi$

proof –

obtain ψ' where $\psi': \langle \psi' : \mathcal{I}_D \rightarrow_D F \mathcal{I}_C \rangle \wedge D.iso \psi'$

using *preserves-unity* by *auto*

have $\langle D.inv \psi' : F \mathcal{I}_C \rightarrow_D \mathcal{I}_D \rangle \wedge D.iso (D.inv \psi')$

using ψ' by *simp*

thus *?thesis* by *auto*

qed

obtain ψ where $\psi: \langle \psi : F \mathcal{I}_C \rightarrow_D \mathcal{I}_D \rangle \wedge D.iso \psi$

using *1* by *blast*

interpret *L: equivalence-functor* $D D \langle \lambda f. (D.cod \iota_1) \otimes_D f \rangle$

proof –

interpret *L: functor* $D D \langle \lambda f. (F \mathcal{I}_C) \otimes_D f \rangle$

using *D.T.fixing-ide-gives-functor-1* by *simp*

interpret *L: endofunctor* $D \langle \lambda f. (F \mathcal{I}_C) \otimes_D f \rangle ..$

interpret ψx : *natural-transformation* $D D \langle \lambda f. (F \mathcal{I}_C) \otimes_D f \rangle \langle \lambda f. \mathcal{I}_D \otimes_D f \rangle$
 $\langle \lambda f. \psi \otimes_D f \rangle$

using ψ *D.T.fixing-arr-gives-natural-transformation-1* [of ψ] by *auto*

interpret ψx : *natural-isomorphism* $D D \langle \lambda f. (F \mathcal{I}_C) \otimes_D f \rangle \langle \lambda f. \mathcal{I}_D \otimes_D f \rangle \langle \lambda f. \psi \otimes_D f \rangle$

apply *unfold-locales* using ψ *D.tensor-preserves-iso* by *simp*

interpret $\iota_D o \psi x$: *vertical-composite* $D D \langle \lambda f. (F \mathcal{I}_C) \otimes_D f \rangle \langle \lambda f. \mathcal{I}_D \otimes_D f \rangle D.map$
 $\langle \lambda f. \psi \otimes_D f \rangle D.l ..$

interpret $\iota_D o \psi x$: *natural-isomorphism* $D D \langle \lambda f. (F \mathcal{I}_C) \otimes_D f \rangle D.map \iota_D o \psi x.map$

using ψx .*natural-isomorphism-axioms* *D.l.natural-isomorphism-axioms*
natural-isomorphisms-compose by *blast*

interpret *L: equivalence-functor* $D D \langle \lambda f. (F \mathcal{I}_C) \otimes_D f \rangle$

using *L.isomorphic-to-identity-is-equivalence* $\iota_D o \psi x$.*natural-isomorphism-axioms*
by *simp*

show *equivalence-functor* $D D \langle \lambda f. (D.cod \iota_1) \otimes_D f \rangle$

using *L.equivalence-functor-axioms* *C.unit-in-hom* by *auto*

qed

interpret *R: equivalence-functor* $D D \langle \lambda f. T_D (f, D.cod \iota_1) \rangle$

proof –

interpret *R: functor* $D D \langle \lambda f. T_D (f, F \mathcal{I}_C) \rangle$

using *D.T.fixing-ide-gives-functor-2* by *simp*

interpret *R: endofunctor* $D \langle \lambda f. T_D (f, F \mathcal{I}_C) \rangle ..$

interpret $x\psi$: *natural-transformation* $D D \langle \lambda f. f \otimes_D (F \mathcal{I}_C) \rangle \langle \lambda f. f \otimes_D \mathcal{I}_D \rangle$
 $\langle \lambda f. f \otimes_D \psi \rangle$

using ψ *D.T.fixing-arr-gives-natural-transformation-2* [of ψ] by *auto*

interpret $x\psi$: *natural-isomorphism* $D D \langle \lambda f. f \otimes_D (F \mathcal{I}_C) \rangle \langle \lambda f. f \otimes_D \mathcal{I}_D \rangle \langle \lambda f. f \otimes_D \psi \rangle$

using ψ *D.tensor-preserves-iso* by (*unfold-locales*, *simp*)

interpret $\varrho_D o x\psi$: *vertical-composite* $D D \langle \lambda f. f \otimes_D (F \mathcal{I}_C) \rangle \langle \lambda f. f \otimes_D \mathcal{I}_D \rangle D.map$
 $\langle \lambda f. f \otimes_D \psi \rangle D.q ..$

interpret $\varrho_D o x\psi$: *natural-isomorphism* $D D \langle \lambda f. f \otimes_D (F \mathcal{I}_C) \rangle D.map \varrho_D o x\psi.map$

using $x\psi$.*natural-isomorphism-axioms* *D.q.natural-isomorphism-axioms*

natural-isomorphisms-compose **by** *blast*

interpret R : *equivalence-functor* $D D \langle \lambda f. f \otimes_D (F \mathcal{I}_C) \rangle$
using R .*isomorphic-to-identity-is-equivalence* ϱ_D *or* ψ .*natural-isomorphism-axioms*
by *simp*

show *equivalence-functor* $D D \langle \lambda f. f \otimes_D (D.\text{cod } \iota_1) \rangle$
using R .*equivalence-functor-axioms* C .*unit-in-hom* **by** *auto*

qed

show *monoidal-category-with-alternate-unit* $D T_D \alpha_D \iota_D \iota_1$
using D .*pentagon* C .*unit-is-iso* C .*unit-in-hom preserves-hom* ι_1 -*is-iso* ι_1 -*in-hom*
by (*unfold-locales*, *auto*)

qed

no-notation D .*tensor* (**infixr** $\langle \otimes_D \rangle$ 53)
notation D . C_1 .*tensor* (**infixr** $\langle \otimes_D \rangle$ 53)
no-notation D .*assoc* ($\langle a_D[-, -, -] \rangle$)
notation D . C_1 .*assoc* ($\langle a_D[-, -, -] \rangle$)
no-notation D .*assoc'* ($\langle a_D^{-1}[-, -, -] \rangle$)
notation D . C_1 .*assoc'* ($\langle a_D^{-1}[-, -, -] \rangle$)
notation D . C_1 .*unity* ($\langle \mathcal{I}_1 \rangle$)
notation D . C_1 .*lunit* ($\langle l_1[-] \rangle$)
notation D . C_1 .*runit* ($\langle r_1[-] \rangle$)

lemma \mathcal{I}_1 -*char* [*simp*]:
shows $\mathcal{I}_1 = F \mathcal{I}_C$
using ι_1 -*in-hom* **by** *auto*

definition ψ
where $\psi \equiv \text{THE } \psi. \langle \psi : \mathcal{I}_D \rightarrow_D F \mathcal{I}_C \rangle \wedge D.\text{iso } \psi \wedge \psi \cdot_D \iota_D = \iota_1 \cdot_D (\psi \otimes_D \psi)$

lemma ψ -*char*:
shows $\langle \psi : \mathcal{I}_D \rightarrow_D F \mathcal{I}_C \rangle$ **and** $D.\text{iso } \psi$ **and** $\psi \cdot_D \iota_D = \iota_1 \cdot_D (\psi \otimes_D \psi)$
and $\exists ! \psi. \langle \psi : \mathcal{I}_D \rightarrow_D F \mathcal{I}_C \rangle \wedge D.\text{iso } \psi \wedge \psi \cdot_D \iota_D = \iota_1 \cdot_D (\psi \otimes_D \psi)$
proof –
show $\exists ! \psi. \langle \psi : \mathcal{I}_D \rightarrow_D F \mathcal{I}_C \rangle \wedge D.\text{iso } \psi \wedge \psi \cdot_D \iota_D = \iota_1 \cdot_D (\psi \otimes_D \psi)$
using D .*unit-unique-upto-unique-iso* ι_1 -*in-hom*
by (*elim D.in-homE*, *auto*)
hence 1: $\langle \psi : \mathcal{I}_D \rightarrow_D F \mathcal{I}_C \rangle \wedge D.\text{iso } \psi \wedge \psi \cdot_D \iota_D = \iota_1 \cdot_D (\psi \otimes_D \psi)$
unfolding ψ -*def*
using *theI'* [*of* $\lambda \psi. \langle \psi : \mathcal{I}_D \rightarrow_D F \mathcal{I}_C \rangle \wedge D.\text{iso } \psi \wedge \psi \cdot_D \iota_D = \iota_1 \cdot_D (\psi \otimes_D \psi)$]
by *fast*
show $\langle \psi : \mathcal{I}_D \rightarrow_D F \mathcal{I}_C \rangle$ **using** 1 **by** *simp*
show $D.\text{iso } \psi$ **using** 1 **by** *simp*
show $\psi \cdot_D \iota_D = \iota_1 \cdot_D (\psi \otimes_D \psi)$ **using** 1 **by** *simp*

qed

lemma ψ -*eqI*:
assumes $\langle f : \mathcal{I}_D \rightarrow_D F \mathcal{I}_C \rangle$ **and** $D.\text{iso } f$ **and** $f \cdot_D \iota_D = \iota_1 \cdot_D (f \otimes_D f)$
shows $f = \psi$
using *assms* ψ -*def* ψ -*char*

the1-equality [of $\lambda f. \llbracket f: \mathcal{I}_D \rightarrow_D F \mathcal{I}_C \rrbracket \wedge D.iso\ f \wedge f \cdot_D \iota_D = \iota_1 \cdot_D (f \otimes_D f) f$]
by simp

lemma *lunit-coherence1*:

assumes *C.ide a*

shows $l_1[F\ a] \cdot_D (\psi \otimes_D F\ a) = l_D[F\ a]$

proof –

have $D.par\ (l_1[F\ a] \cdot_D (\psi \otimes_D F\ a))\ l_D[F\ a]$

using *assms D.C1.lunit-in-hom D.tensor-in-hom D.lunit-in-hom ψ -char(1)*

by *auto*

The upper left triangle in the following diagram commutes.

$$\begin{array}{ccc}
 \mathcal{I} \otimes Fa & \xrightarrow{\psi \otimes Fa} & F\mathcal{I} \otimes Fa \\
 \uparrow \mathcal{I} \otimes l_1[Fa] & & \uparrow F\mathcal{I} \otimes l_1[Fa] \\
 \mathcal{I} \otimes (F\mathcal{I} \otimes Fa) & & \\
 \uparrow \mathcal{I} \otimes (\psi \otimes Fa) & \xrightarrow{\psi \otimes (F\mathcal{I} \otimes Fa)} & \\
 \mathcal{I} \otimes (\mathcal{I} \otimes Fa) & \xrightarrow{\psi \otimes (\psi \otimes Fa)} & F\mathcal{I} \otimes (F\mathcal{I} \otimes Fa) \\
 \uparrow \mathcal{I} \otimes [Fa] & & \uparrow \\
 (\mathcal{I} \otimes \mathcal{I}) \otimes Fa & \xrightarrow{(\psi \otimes \psi) \otimes Fa} & (F\mathcal{I} \otimes F\mathcal{I}) \otimes Fa \\
 \uparrow \iota \otimes Fa & & \uparrow \iota_1 \otimes Fa \\
 \mathcal{I} \otimes Fa & & F\mathcal{I} \otimes Fa \\
 \uparrow a[\mathcal{I}, \mathcal{I}, Fa] & & \uparrow a[F\mathcal{I}, F\mathcal{I}, Fa]
 \end{array}$$

moreover have $(\mathcal{I}_D \otimes_D l_1[F\ a]) \cdot_D (\mathcal{I}_D \otimes_D \psi \otimes_D F\ a) = \mathcal{I}_D \otimes_D l_D[F\ a]$

proof –

have $(\mathcal{I}_D \otimes_D l_1[F\ a]) \cdot_D (\mathcal{I}_D \otimes_D \psi \otimes_D F\ a)$

$= (\mathcal{I}_D \otimes_D l_1[F\ a]) \cdot_D (D.inv\ \psi \otimes_D F\ \mathcal{I}_C \otimes_D F\ a) \cdot_D (\psi \otimes_D \psi \otimes_D F\ a)$

using *assms ψ -char(1-2) D.interchange [of D.inv ψ] D.comp-cod-arr*

D.inv-is-inverse D.comp-inv-arr

by *(elim D.in-homE, simp)*

also have $\dots = (D.inv\ \psi \otimes_D F\ a) \cdot_D (F\ \mathcal{I}_C \otimes_D l_1[F\ a]) \cdot_D (\psi \otimes_D \psi \otimes_D F\ a)$

proof –

have $(\mathcal{I}_D \otimes_D l_1[F\ a]) \cdot_D (D.inv\ \psi \otimes_D F\ \mathcal{I}_C \otimes_D F\ a) =$

$(D.inv\ \psi \otimes_D F\ a) \cdot_D (F\ \mathcal{I}_C \otimes_D l_1[F\ a])$

using *assms ψ -char(1-2) D.interchange [of \mathcal{I}_D] D.interchange [of D.inv ψ]*

D.comp-arr-dom D.comp-cod-arr

by *(elim D.in-homE, auto)*

thus *?thesis*

using *assms ψ -char(1-2) D.inv-in-hom*

D.comp-permute [of $\mathcal{I}_D \otimes_D l_1[F\ a]$ D.inv $\psi \otimes_D F\ \mathcal{I}_C \otimes_D F\ a$

D.inv $\psi \otimes_D F\ a$ F $\mathcal{I}_C \otimes_D l_1[F\ a]$]

by (*elim D.in-homE*, *auto*)
qed
also have ... = $(D.inv \psi \otimes_D F a) \cdot_D (\iota_1 \otimes_D F a) \cdot_D D.inv \mathfrak{a}_D[F \mathcal{I}_C, F \mathcal{I}_C, F a] \cdot_D$
 $(\psi \otimes_D \psi \otimes_D F a)$
 using *assms* ψ -char(1-2) *D.C1.lunit-char*(2) *D.comp-assoc* **by** *auto*
also have ... = $((D.inv \psi \otimes_D F a) \cdot_D (\iota_1 \otimes_D F a) \cdot_D ((\psi \otimes_D \psi) \otimes_D F a)) \cdot_D$
 $D.inv \mathfrak{a}_D[\mathcal{I}_D, \mathcal{I}_D, F a]$
 using *assms* ψ -char(1-2) *D.assoc'-naturality* [of $\psi \psi F a$] *D.comp-assoc* **by** *auto*
also have ... = $(\iota_D \otimes_D F a) \cdot_D D.inv \mathfrak{a}_D[\mathcal{I}_D, \mathcal{I}_D, F a]$
proof –
have $(D.inv \psi \otimes_D F a) \cdot_D (\iota_1 \otimes_D F a) \cdot_D ((\psi \otimes_D \psi) \otimes_D F a) = \iota_D \otimes_D F a$
proof –
have $(D.inv \psi \otimes_D F a) \cdot_D (\iota_1 \otimes_D F a) \cdot_D ((\psi \otimes_D \psi) \otimes_D F a) =$
 $D.inv \psi \cdot_D \psi \cdot_D \iota_D \otimes_D F a$
 using *assms* ψ -char(1-3) ι_1 -in-hom *D.interchange*
 by (*elim D.in-homE*, *auto*)
also have ... = $\iota_D \otimes_D F a$
 using *assms* ψ -char(1-2) *D.inv-is-inverse* *D.comp-inv-arr* *D.comp-cod-arr*
 $D.comp-reduce$ *D.unit-in-hom*
 by (*elim D.in-homE*, *auto*)
finally show *?thesis* **by** *blast*
qed
thus *?thesis* **by** *simp*
qed
also have ... = $\mathcal{I}_D \otimes_D 1_D[F a]$
 using *assms* *D.lunit-char* **by** *simp*
finally show *?thesis* **by** *blast*
qed
ultimately show *?thesis*
 using *D.L.is-faithful* [of $1_1[F a] \cdot_D (\psi \otimes_D F a) 1_D[F a]$] **by** *force*
qed

lemma *lunit-coherence2*:
assumes *C.ide a*
shows $F 1_C[a] \cdot_D \varphi(\mathcal{I}_C, a) = 1_1[F a]$
proof –

We show that the lower left triangle in the following diagram commutes.

$$\begin{array}{ccccc}
(F\mathcal{I} \otimes F\mathcal{I}) \otimes Fa & \xrightarrow{\phi(\mathcal{I}, \mathcal{I}) \otimes Fa} & F(\mathcal{I} \otimes \mathcal{I}) \otimes Fa & & \\
\downarrow a[F\mathcal{I}, F\mathcal{I}, Fa] & \searrow \iota_1 \otimes Fa & \swarrow F\iota \otimes Fa & & \downarrow \phi(\mathcal{I} \otimes \mathcal{I}, a) \\
F\mathcal{I} \otimes (F\mathcal{I} \otimes Fa) & \xrightarrow{F\mathcal{I} \otimes l_1[Fa]} & F\mathcal{I} \otimes Fa & \xrightarrow{\phi(\mathcal{I}, a)} & F(\mathcal{I} \otimes a) \leftarrow F((\mathcal{I} \otimes \mathcal{I}) \otimes a) \\
\downarrow F\mathcal{I} \otimes \phi(\mathcal{I}, a) & \swarrow F\mathcal{I} \otimes F l[a] & & \swarrow F(\mathcal{I} \otimes l[a]) & \downarrow Fa[\mathcal{I}, \mathcal{I}, a] \\
F\mathcal{I} \otimes F(\mathcal{I} \otimes a) & \xrightarrow{\phi(\mathcal{I}, \mathcal{I} \otimes a)} & F(\mathcal{I} \otimes (\mathcal{I} \otimes a)) & &
\end{array}$$

have $(F \mathcal{I}_C \otimes_D F l_C[a]) \cdot_D (F \mathcal{I}_C \otimes_D \varphi(\mathcal{I}_C, a)) = F \mathcal{I}_C \otimes_D l_1[F a]$

proof –

$$\begin{aligned}
& \text{have } (F \mathcal{I}_C \otimes_D F l_C[a]) \cdot_D (F \mathcal{I}_C \otimes_D \varphi(\mathcal{I}_C, a)) \\
& = (F \mathcal{I}_C \otimes_D F l_C[a]) \cdot_D D.inv(\varphi(\mathcal{I}_C, \mathcal{I}_C \otimes_C a)) \cdot_D F a_C[\mathcal{I}_C, \mathcal{I}_C, a] \cdot_D \\
& \quad \varphi(\mathcal{I}_C \otimes_C \mathcal{I}_C, a) \cdot_D (\varphi(\mathcal{I}_C, \mathcal{I}_C) \otimes_D F a) \cdot_D D.inv a_D[F \mathcal{I}_C, F \mathcal{I}_C, F a]
\end{aligned}$$

proof –

$$\begin{aligned}
& \text{have } D.inv(\varphi(\mathcal{I}_C, \mathcal{I}_C \otimes_C a)) \cdot_D F a_C[\mathcal{I}_C, \mathcal{I}_C, a] \cdot_D \varphi(\mathcal{I}_C \otimes_C \mathcal{I}_C, a) \cdot_D \\
& \quad (\varphi(\mathcal{I}_C, \mathcal{I}_C) \otimes_D F a) \\
& = (F \mathcal{I}_C \otimes_D \varphi(\mathcal{I}_C, a)) \cdot_D a_D[F \mathcal{I}_C, F \mathcal{I}_C, F a]
\end{aligned}$$

using *assms* φ -in-hom *assoc-coherence* *D.invert-side-of-triangle(1)* **by** *simp*

hence $F \mathcal{I}_C \otimes_D \varphi(\mathcal{I}_C, a)$

$$\begin{aligned}
& = (D.inv(\varphi(\mathcal{I}_C, \mathcal{I}_C \otimes_C a)) \cdot_D F a_C[\mathcal{I}_C, \mathcal{I}_C, a] \cdot_D \varphi(\mathcal{I}_C \otimes_C \mathcal{I}_C, a) \cdot_D \\
& \quad (\varphi(\mathcal{I}_C, \mathcal{I}_C) \otimes_D F a)) \cdot_D D.inv a_D[F \mathcal{I}_C, F \mathcal{I}_C, F a]
\end{aligned}$$

using *assms* φ -in-hom *D.invert-side-of-triangle(2)* **by** *simp*

thus *?thesis*

using *D.comp-assoc* **by** *simp*

qed

$$\begin{aligned}
& \text{also have } \dots = (F \mathcal{I}_C \otimes_D F l_C[a]) \cdot_D D.inv(\varphi(\mathcal{I}_C, \mathcal{I}_C \otimes_C a)) \cdot_D \\
& \quad (D.inv(F(\mathcal{I}_C \otimes_C l_C[a])) \cdot_D F(\iota_C \otimes_C a)) \cdot_D \\
& \quad \varphi(\mathcal{I}_C \otimes_C \mathcal{I}_C, a) \cdot_D (\varphi(\mathcal{I}_C, \mathcal{I}_C) \otimes_D F a) \cdot_D \\
& \quad D.inv a_D[F \mathcal{I}_C, F \mathcal{I}_C, F a]
\end{aligned}$$

proof –

$$\text{have } 1: F(\mathcal{I}_C \otimes_C l_C[a]) = F(\iota_C \otimes_C a) \cdot_D D.inv(F a_C[\mathcal{I}_C, \mathcal{I}_C, a])$$

using *assms* *C.lunit-char(1-2)* *C.unit-in-hom preserves-inv* **by** *auto*

$$\text{hence } F a_C[\mathcal{I}_C, \mathcal{I}_C, a] = D.inv(F(\mathcal{I}_C \otimes_C l_C[a])) \cdot_D F(\iota_C \otimes_C a)$$

proof –

$$\begin{aligned}
& \text{have } F a_C[\mathcal{I}_C, \mathcal{I}_C, a] \cdot_D D.inv(F(\iota_C \otimes_C a)) \\
& = D.inv(F(\iota_C \otimes_C a)) \cdot_D D.inv(F a_C[\mathcal{I}_C, \mathcal{I}_C, a])
\end{aligned}$$

using *assms 1 preserves-iso C.ide-is-iso C.unit-is-iso C.ide-unity C.iso-assoc*
C.iso-lunit C.tensor-preserved-iso D.inv-comp D.inv-inv
D.iso-inv-iso D.iso-is-arr
by *metis*
thus *?thesis*
using *assms 1 preserves-iso C.ide-is-iso C.unit-is-iso C.ide-unity C.iso-assoc*
C.iso-lunit C.tensor-preserved-iso D.inv-comp D.inv-inv
D.iso-inv-iso D.iso-is-arr D.invert-side-of-triangle(2)
by *metis*
qed
thus *?thesis by argo*
qed
also have ... = $(F \mathcal{I}_C \otimes_D F \mathbb{1}_C[a]) \cdot_D D.inv (\varphi (\mathcal{I}_C, \mathcal{I}_C \otimes_C a)) \cdot_D$
 $D.inv (F (\mathcal{I}_C \otimes_C \mathbb{1}_C[a])) \cdot_D (F (\iota_C \otimes_C a)) \cdot_D \varphi (\mathcal{I}_C \otimes_C \mathcal{I}_C, a) \cdot_D$
 $(\varphi (\mathcal{I}_C, \mathcal{I}_C) \otimes_D F a) \cdot_D D.inv \mathfrak{a}_D[F \mathcal{I}_C, F \mathcal{I}_C, F a]$
using *D.comp-assoc by auto*
also have ... = $(F \mathcal{I}_C \otimes_D F \mathbb{1}_C[a]) \cdot_D D.inv (\varphi (\mathcal{I}_C, \mathcal{I}_C \otimes_C a)) \cdot_D$
 $D.inv (F (\mathcal{I}_C \otimes_C \mathbb{1}_C[a])) \cdot_D (\varphi (\mathcal{I}_C, a)) \cdot_D (F \iota_C \otimes_D F a) \cdot_D$
 $(\varphi (\mathcal{I}_C, \mathcal{I}_C) \otimes_D F a) \cdot_D D.inv \mathfrak{a}_D[F \mathcal{I}_C, F \mathcal{I}_C, F a]$
using *assms $\varphi.naturality$ [of (ι_C, a)] C.unit-in-hom by auto*
also have ... = $(F \mathcal{I}_C \otimes_D F \mathbb{1}_C[a]) \cdot_D D.inv (\varphi (\mathcal{I}_C, \mathcal{I}_C \otimes_C a)) \cdot_D$
 $D.inv (F (\mathcal{I}_C \otimes_C \mathbb{1}_C[a])) \cdot_D \varphi (\mathcal{I}_C, a) \cdot_D$
 $((F \iota_C \otimes_D F a) \cdot_D (\varphi (\mathcal{I}_C, \mathcal{I}_C) \otimes_D F a)) \cdot_D$
 $D.inv \mathfrak{a}_D[F \mathcal{I}_C, F \mathcal{I}_C, F a]$
using *D.comp-assoc by auto*
also have ... = $(F \mathcal{I}_C \otimes_D F \mathbb{1}_C[a]) \cdot_D D.inv (\varphi (\mathcal{I}_C, \mathcal{I}_C \otimes_C a)) \cdot_D$
 $D.inv (F (\mathcal{I}_C \otimes_C \mathbb{1}_C[a])) \cdot_D \varphi (\mathcal{I}_C, a) \cdot_D (\iota_1 \otimes_D F a) \cdot_D$
 $D.inv \mathfrak{a}_D[F \mathcal{I}_C, F \mathcal{I}_C, F a]$
using *assms D.interchange C.unit-in-hom by auto*
also have ... = $(F \mathcal{I}_C \otimes_D F \mathbb{1}_C[a]) \cdot_D D.inv (\varphi (\mathcal{I}_C, \mathcal{I}_C \otimes_C a)) \cdot_D$
 $D.inv (F (\mathcal{I}_C \otimes_C \mathbb{1}_C[a])) \cdot_D \varphi (\mathcal{I}_C, a) \cdot_D$
 $((F \mathcal{I}_C \otimes_D \mathbb{1}_1[F a]) \cdot_D \mathfrak{a}_D[F \mathcal{I}_C, F \mathcal{I}_C, F a]) \cdot_D$
 $D.inv \mathfrak{a}_D[F \mathcal{I}_C, F \mathcal{I}_C, F a]$
proof –
have $(\iota_1 \otimes_D F a) \cdot_D \mathfrak{a}_D^{-1}[F \mathcal{I}_C, F \mathcal{I}_C, F a] = F \mathcal{I}_C \otimes_D \mathbb{1}_1[F a]$
using *assms D.C₁.lunit-char [of F a] by auto*
thus *?thesis*
using *assms D.inv-is-inverse ι_1 -in-hom φ -in-hom D.invert-side-of-triangle(2)*
by *simp*
qed
also have ... = $(F \mathcal{I}_C \otimes_D F \mathbb{1}_C[a]) \cdot_D$
 $(D.inv (\varphi (\mathcal{I}_C, \mathcal{I}_C \otimes_C a)) \cdot_D D.inv (F (\mathcal{I}_C \otimes_C \mathbb{1}_C[a])) \cdot_D \varphi (\mathcal{I}_C, a)) \cdot_D$
 $(F \mathcal{I}_C \otimes_D \mathbb{1}_1[F a])$
using *assms D.comp-arr-dom [of F $\mathcal{I}_C \otimes_D \mathbb{1}_1[F a]$] D.comp-assoc by auto*
also have ... = $(F \mathcal{I}_C \otimes_D F \mathbb{1}_C[a]) \cdot_D D.inv (F \mathcal{I}_C \otimes_D F \mathbb{1}_C[a]) \cdot_D (F \mathcal{I}_C \otimes_D \mathbb{1}_1[F a])$
proof –
have $D.inv (F \mathcal{I}_C \otimes_D F \mathbb{1}_C[a])$
 $= D.inv (D.inv (\varphi (\mathcal{I}_C, a)) \cdot_D F (\mathcal{I}_C \otimes_C \mathbb{1}_C[a]) \cdot_D \varphi (\mathcal{I}_C, \mathcal{I}_C \otimes_C a))$
using *assms $\varphi.naturality$ [of $(\mathcal{I}_C, \mathbb{1}_C[a])$] D.invert-side-of-triangle(1) by simp*

also have ... = $D.\text{inv } (\varphi (\mathcal{I}_C, \mathcal{I}_C \otimes_C a)) \cdot_D D.\text{inv } (F (\mathcal{I}_C \otimes_C \mathbb{1}_C[a])) \cdot_D \varphi (\mathcal{I}_C, a)$
using *assms* $D.\text{inv-comp } D.\text{inv-is-inverse } D.\text{isos-compose } D.\text{comp-assoc}$
by *simp*
finally have $D.\text{inv } (F \mathcal{I}_C \otimes_D F \mathbb{1}_C[a])$
= $D.\text{inv } (\varphi (\mathcal{I}_C, \mathcal{I}_C \otimes_C a)) \cdot_D D.\text{inv } (F (\mathcal{I}_C \otimes_C \mathbb{1}_C[a])) \cdot_D \varphi (\mathcal{I}_C, a)$
by *blast*
thus *?thesis* **by** *argo*
qed
also have ... = $((F \mathcal{I}_C \otimes_D F \mathbb{1}_C[a]) \cdot_D D.\text{inv } (F \mathcal{I}_C \otimes_D F \mathbb{1}_C[a])) \cdot_D (F \mathcal{I}_C \otimes_D \mathbb{1}_1[F a])$
using *assms* $D.\text{tensor-preserves-iso } D.\text{comp-assoc}$ **by** *simp*
also have ... = $F \mathcal{I}_C \otimes_D \mathbb{1}_1[F a]$
using *assms* $D.\text{tensor-preserves-iso } D.\text{comp-arr-inv } D.\text{inv-is-inverse } D.\text{comp-cod-arr}$
 $D.\text{interchange}$
by *simp*
finally show *?thesis* **by** *blast*
qed
hence $F \mathcal{I}_C \otimes_D F \mathbb{1}_C[a] \cdot_D \varphi (\mathcal{I}_C, a) = F \mathcal{I}_C \otimes_D \mathbb{1}_1[F a]$
using *assms* $\varphi\text{-in-hom } D.\text{interchange}$ **by** *simp*
moreover have $D.\text{par } (F \mathbb{1}_C[a] \cdot_D \varphi (\mathcal{I}_C, a)) \mathbb{1}_1[F a]$
using *assms* $\varphi\text{-in-hom}$ **by** *simp*
ultimately show *?thesis*
using $D.C_1.L.\text{is-faithful } [of F \mathbb{1}_C[a] \cdot_D \varphi (\mathcal{I}_C, a) \mathbb{1}_1[F a]]$ **by** *simp*
qed

Combining the two previous lemmas yields the coherence result we seek. This is the condition that is traditionally taken as part of the definition of monoidal functor.

lemma *lunit-coherence*:

assumes $C.\text{ide } a$

shows $\mathbb{1}_D[F a] = F \mathbb{1}_C[a] \cdot_D \varphi (\mathcal{I}_C, a) \cdot_D (\psi \otimes_D F a)$

proof –

have $\mathbb{1}_D[F a] \cdot_D D.\text{inv } (\psi \otimes_D F a) = \mathbb{1}_1[F a]$

using *assms* $\text{lunit-coherence1 } \psi\text{-char}(2)$

$D.\text{invert-side-of-triangle}(2) [of \mathbb{1}_D[F a] \mathbb{1}_1[F a] \psi \otimes_D F a]$

by *auto*

also have ... = $F \mathbb{1}_C[a] \cdot_D \varphi (\mathcal{I}_C, a)$

using *assms* lunit-coherence2 **by** *simp*

finally have $\mathbb{1}_D[F a] \cdot_D D.\text{inv } (\psi \otimes_D F a) = F \mathbb{1}_C[a] \cdot_D \varphi (\mathcal{I}_C, a)$

by *blast*

hence $\mathbb{1}_D[F a] = (F \mathbb{1}_C[a] \cdot_D \varphi (\mathcal{I}_C, a)) \cdot_D (\psi \otimes_D F a)$

using *assms* $\psi\text{-char}(2) \varphi\text{-in-hom}$

$D.\text{invert-side-of-triangle}(2) [of F \mathbb{1}_C[a] \cdot_D \varphi (\mathcal{I}_C, a) \mathbb{1}_D[F a] D.\text{inv } (\psi \otimes_D F a)]$

by *simp*

thus *?thesis*

using *assms* $\psi\text{-char}(1) D.\text{comp-assoc}$ **by** *auto*

qed

We now want to obtain the corresponding result for the right unitor. To avoid a repetition of what would amount to essentially the same tedious diagram chases that were carried out above, we instead show here that F becomes a monoidal functor from

the opposite of C to the opposite of D , with $\lambda f. \varphi (snd f, fst f)$ as the structure map. The fact that in the opposite monoidal categories the left and right unitors are exchanged then permits us to obtain the result for the right unitor from the result already proved for the left unitor.

interpretation C' : *opposite-monoidal-category* $C T_C \alpha_C \iota_C ..$
interpretation D' : *opposite-monoidal-category* $D T_D \alpha_D \iota_D ..$
interpretation $T_D' oFF$: *composite-functor* $C.CC.comp D.CC.comp D.FF.map D'.T ..$
interpretation $FoT_{C'}$: *composite-functor* $C.CC.comp C D C'.T F ..$
interpretation φ' : *natural-transformation* $C.CC.comp D T_D' oFF.map FoT_{C'}.map$
 $\langle \lambda f. \varphi (snd f, fst f) \rangle$
using $\varphi.naturality1 \varphi.naturality2 \varphi.extensionality$ **by** $(unfold-locales, auto)$
interpretation φ' : *natural-isomorphism* $C.CC.comp D T_D' oFF.map FoT_{C'}.map$
 $\langle \lambda f. \varphi (snd f, fst f) \rangle$
by $(unfold-locales, simp)$
interpretation F' : *monoidal-functor* $C C'.T C'.\alpha \iota_C D D'.T D'.\alpha \iota_D F \langle \lambda f. \varphi (snd f, fst f) \rangle$
using *preserves-unity* **apply** $(unfold-locales; simp)$
proof –
fix $a b c$
assume $a: C.ide a$ **and** $b: C.ide b$ **and** $c: C.ide c$
have $(\varphi (c \otimes_C b, a) \cdot_D (\varphi (c, b) \otimes_D F a)) \cdot_D a_D^{-1}[F c, F b, F a] =$
 $F (C.assoc' c b a) \cdot_D \varphi (c, b \otimes_C a) \cdot_D (F c \otimes_D \varphi (b, a))$
proof –
have $D.seq (F a_C[c, b, a]) (\varphi (c \otimes_C b, a) \cdot_D (\varphi (c, b) \otimes_D F a))$
using $a b c \varphi\text{-in-hom}$ **by** *simp*
moreover have $D.seq (\varphi (c, b \otimes_C a) \cdot_D (F c \otimes_D \varphi (b, a))) a_D[F c, F b, F a]$
using $a b c \varphi\text{-in-hom}$ **by** *simp*
moreover have
 $F a_C[c, b, a] \cdot_D \varphi (c \otimes_C b, a) \cdot_D (\varphi (c, b) \otimes_D F a) =$
 $(\varphi (c, b \otimes_C a) \cdot_D (F c \otimes_D \varphi (b, a))) \cdot_D a_D[F c, F b, F a]$
using $a b c$ *assoc-coherence* $D.comp-assoc$ **by** *simp*
moreover have $D.iso (F a_C[c, b, a])$
using $a b c$ **by** *simp*
moreover have $D.iso a_D[F c, F b, F a]$
using $a b c$ **by** *simp*
moreover have $D.inv (F a_C[c, b, a]) = F (C.assoc' c b a)$
using $a b c$ *preserves-inv* **by** *simp*
ultimately show *?thesis*
using $D.invert-opposite-sides-of-square$ **by** *simp*
qed
thus $F (C.assoc' c b a) \cdot_D \varphi (c, b \otimes_C a) \cdot_D (F c \otimes_D \varphi (b, a)) =$
 $\varphi (c \otimes_C b, a) \cdot_D (\varphi (c, b) \otimes_D F a) \cdot_D a_D^{-1}[F c, F b, F a]$
using $D.comp-assoc$ **by** *simp*
qed

lemma *induces-monoidal-functor-between-opposites:*
shows *monoidal-functor* $C C'.T C'.\alpha \iota_C D D'.T D'.\alpha \iota_D F (\lambda f. \varphi (snd f, fst f))$
..

```

lemma runit-coherence:
assumes C.ide a
shows  $r_D[F a] = F \ r_C[a] \cdot_D \varphi(a, \mathcal{I}_C) \cdot_D (F a \otimes_D \psi)$ 
proof –
  have  $C'.lunit\ a = r_C[a]$ 
    using assms C'.lunit-simp by simp
  moreover have  $D'.lunit\ (F\ a) = r_D[F\ a]$ 
    using assms D'.lunit-simp by simp
  moreover have  $F'.\psi = \psi$ 
proof (intro \psi-eqI)
  show  $\langle F'.\psi : D'.unity \rightarrow_D F\ C'.unity \rangle$  using F'.\psi-char(1) by simp
  show D.iso F'.\psi using F'.\psi-char(2) by simp
  show  $F'.\psi \cdot_D \iota_D = \iota_1 \cdot_D (F'.\psi \otimes_D F'.\psi)$  using F'.\psi-char(3) by simp
qed
  moreover have  $D'.lunit\ (F\ a) = F\ (C'.lunit\ a) \cdot_D \varphi(a, C'.unity) \cdot_D (F\ a \otimes_D F'.\psi)$ 
    using assms F'.lunit-coherence by simp
  ultimately show ?thesis by simp
qed

```

end

3.1 Strict Monoidal Functor

A strict monoidal functor preserves the monoidal structure “on the nose”.

```

locale strict-monoidal-functor =
  C: monoidal-category C T_C \alpha_C \iota_C +
  D: monoidal-category D T_D \alpha_D \iota_D +
  functor C D F
for  $C :: 'c\ comp$  (infixr  $\langle \cdot_C \rangle$  55)
and  $T_C :: 'c * 'c \Rightarrow 'c$ 
and  $\alpha_C :: 'c * 'c * 'c \Rightarrow 'c$ 
and  $\iota_C :: 'c$ 
and  $D :: 'd\ comp$  (infixr  $\langle \cdot_D \rangle$  55)
and  $T_D :: 'd * 'd \Rightarrow 'd$ 
and  $\alpha_D :: 'd * 'd * 'd \Rightarrow 'd$ 
and  $\iota_D :: 'd$ 
and  $F :: 'c \Rightarrow 'd +$ 
assumes strictly-preserves-\iota:  $F\ \iota_C = \iota_D$ 
and strictly-preserves-T:  $\llbracket C.arr\ f; C.arr\ g \rrbracket \Longrightarrow F\ (T_C\ (f, g)) = T_D\ (F\ f, F\ g)$ 
and strictly-preserves-\alpha-ide:  $\llbracket C.ide\ a; C.ide\ b; C.ide\ c \rrbracket \Longrightarrow$ 
 $F\ (\alpha_C\ (a, b, c)) = \alpha_D\ (F\ a, F\ b, F\ c)$ 

```

begin

```

notation C.tensor (infixr  $\langle \otimes_C \rangle$  53)
and C.unity ( $\langle \mathcal{I}_C \rangle$ )
and C.lunit ( $\langle \downarrow_C[-] \rangle$ )
and C.runit ( $\langle r_C[-] \rangle$ )
and C.assoc ( $\langle a_C[-, -, -] \rangle$ )

```

and $D.tensor$ (**infixr** $\langle \otimes_D \rangle$ 53)
and $D.unital$ ($\langle \mathcal{I}_D \rangle$)
and $D.lunit$ ($\langle \mathcal{L}_D[-] \rangle$)
and $D.runit$ ($\langle \mathcal{R}_D[-] \rangle$)
and $D.assoc$ ($\langle \mathcal{A}_D[-, -, -] \rangle$)

lemma *strictly-preserves-tensor*:

assumes $C.arr\ f$ **and** $C.arr\ g$
shows $F(f \otimes_C g) = Ff \otimes_D Fg$
using *assms strictly-preserves-T by blast*

lemma *strictly-preserves- α* :

assumes $C.arr\ f$ **and** $C.arr\ g$ **and** $C.arr\ h$
shows $F(\alpha_C(f, g, h)) = \alpha_D(Ff, Fg, Fh)$
proof –
have $F(\alpha_C(f, g, h)) = F((f \otimes_C g \otimes_C h) \cdot_C \alpha_C(C.dom\ f, C.dom\ g, C.dom\ h))$
using *assms C.alpha.naturality1 [of (f, g, h)] C.T.ToCT-simp by force*
also have $\dots = (Ff \otimes_D Fg \otimes_D Fh) \cdot_D \alpha_D(D.dom(Ff), D.dom(Fg), D.dom(Fh))$
using *assms strictly-preserves-alpha-ide strictly-preserves-tensor by simp*
also have $\dots = \alpha_D(Ff, Fg, Fh)$
using *assms D.alpha.naturality1 [of (Ff, Fg, Fh)] by simp*
finally show *?thesis by blast*
qed

lemma *strictly-preserves-unity*:

shows $F\ \mathcal{I}_C = \mathcal{I}_D$
using *C.unit-in-hom strictly-preserves- ι by auto*

lemma *strictly-preserves-assoc*:

assumes $C.arr\ a$ **and** $C.arr\ b$ **and** $C.arr\ c$
shows $F\ \mathcal{A}_C[a, b, c] = \mathcal{A}_D[Fa, Fb, Fc]$
using *assms strictly-preserves- α by simp*

lemma *strictly-preserves-lunit*:

assumes $C.ide\ a$
shows $F\ \mathcal{L}_C[a] = \mathcal{L}_D[Fa]$
proof –
let $?P = \lambda f. f \in C.hom(\mathcal{I}_C \otimes_C a)\ a \wedge \mathcal{I}_C \otimes_C f = (\iota_C \otimes_C a) \cdot_C C.assoc'\ \mathcal{I}_C\ \mathcal{I}_C\ a$
let $?Q = \lambda f. f \in D.hom(\mathcal{I}_D \otimes_D Fa)\ (Fa) \wedge$
 $\mathcal{I}_D \otimes_D f = (\iota_D \otimes_D Fa) \cdot_D D.assoc'\ \mathcal{I}_D\ \mathcal{I}_D\ (Fa)$
have 1: $?P\ \mathcal{L}_C[a]$ **using** *assms C.lunit-char by simp*
hence $?Q\ (F\ \mathcal{L}_C[a])$
proof –
have $F\ \mathcal{L}_C[a] \in D.hom(\mathcal{I}_D \otimes_D Fa)\ (Fa)$
using *assms 1 strictly-preserves-unity strictly-preserves-tensor by auto*
moreover have
 $F((\iota_C \otimes_C a) \cdot_C C.assoc'\ \mathcal{I}_C\ \mathcal{I}_C\ a) = (\iota_D \otimes_D Fa) \cdot_D D.assoc'\ \mathcal{I}_D\ \mathcal{I}_D\ (Fa)$
using *assms 1 strictly-preserves- ι strictly-preserves-assoc strictly-preserves-unity*
strictly-preserves-tensor preserves-inv C.unit-in-hom


```

    by auto
  moreover have  $\mathcal{I}_D \otimes_D F \mathbb{1}_C[a] = F (\mathcal{I}_C \otimes_C \mathbb{1}_C[a])$ 
    using assms strictly-preserves-unity strictly-preserves-tensor by simp
  ultimately show ?thesis
    using assms C.lunit-char(2) by simp
qed
thus ?thesis using assms D.lunit-eqI by simp
qed

```

lemma *strictly-preserves-runit:*

assumes *C.ide a*

shows $F \mathbb{r}_C[a] = \mathbb{r}_D[F a]$

proof –

let $?P = \lambda f. f \in C.\text{hom} (a \otimes_C \mathcal{I}_C) a \wedge f \otimes_C \mathcal{I}_C = (a \otimes_C \iota_C) \cdot_C C.\text{assoc } a \mathcal{I}_C \mathcal{I}_C$

let $?Q = \lambda f. f \in D.\text{hom} (F a \otimes_D \mathcal{I}_D) (F a) \wedge$

$f \otimes_D \mathcal{I}_D = (F a \otimes_D \iota_D) \cdot_D D.\text{assoc} (F a) \mathcal{I}_D \mathcal{I}_D$

have 1: $?P \mathbb{r}_C[a]$ using *assms C.runit-char* by simp

hence $?Q (F \mathbb{r}_C[a])$

proof –

have $F \mathbb{r}_C[a] \in D.\text{hom} (F a \otimes_D \mathcal{I}_D) (F a)$

using *assms 1 strictly-preserves-unity strictly-preserves-tensor* by auto

moreover have $F ((a \otimes_C \iota_C) \cdot_C C.\text{assoc } a \mathcal{I}_C \mathcal{I}_C)$

$= (F a \otimes_D \iota_D) \cdot_D D.\text{assoc} (F a) \mathcal{I}_D \mathcal{I}_D$

using *assms 1 strictly-preserves-ι strictly-preserves-assoc strictly-preserves-unity strictly-preserves-tensor preserves-inv C.unit-in-hom*

by auto

moreover have $F \mathbb{r}_C[a] \otimes_D \mathcal{I}_D = F (\mathbb{r}_C[a] \otimes_C \mathcal{I}_C)$

using *assms strictly-preserves-unity strictly-preserves-tensor* by simp

ultimately show *?thesis*

using *assms C.runit-char(2)* by simp

qed

thus *?thesis* using *assms D.runit-eqI* by simp

qed

The following are used to simplify the expression of the sublocale relationship between *strict-monoidal-functor* and *monoidal-functor*, as the definition of the latter mentions the structure map φ . For a strict monoidal functor, this is an identity transformation.

interpretation *FF: product-functor C C D D F F ..*

interpretation *FoTC: composite-functor C.CC.comp C D TC F ..*

interpretation *TDoFF: composite-functor C.CC.comp D.CC.comp D FF.map TD ..*

lemma *structure-is-trivial:*

shows $T_D \circ FF.\text{map} = FoTC.\text{map}$

proof

fix x

have $C.CC.\text{arr } x \implies T_D \circ FF.\text{map } x = FoTC.\text{map } x$

proof –

assume $x: C.CC.\text{arr } x$

have $T_D \circ FF.\text{map } x = F (\text{fst } x) \otimes_D F (\text{snd } x)$

```

    using x by simp
  also have ... = FoTC.map x
    using x strictly-preserves-tensor [of fst x snd x] by simp
  finally show T_D o FF.map x = FoTC.map x by simp
qed
moreover have ¬ C.CC.arr x ⇒ T_D o FF.map x = FoTC.map x
  using T_D o FF.extensionality FoTC.extensionality by simp
ultimately show T_D o FF.map x = FoTC.map x by blast
qed

```

abbreviation φ where $\varphi \equiv T_D o FF.map$

lemma *structure-naturalityisomorphism*:

```

shows natural-isomorphism C.CC.comp D T_D o FF.map FoTC.map  $\varphi$ 
  using T_D o FF.as-nat-iso.natural-isomorphism-axioms structure-is-trivial by force

```

end

A strict monoidal functor is a monoidal functor.

sublocale *strict-monoidal-functor* \subseteq *monoidal-functor* C T_C α_C ι_C D T_D α_D ι_D F φ

proof –

```

interpret FF: product-functor C C D D F F ..
interpret FoTC: composite-functor C.CC.comp C D T_C F ..
interpret T_D o FF: composite-functor C.CC.comp D.CC.comp D FF.map T_D ..
interpret  $\varphi$ : natural-isomorphism C.CC.comp D T_D o FF.map FoTC.map  $\varphi$ 
  using structure-naturalityisomorphism by simp
show monoidal-functor C T_C  $\alpha_C$   $\iota_C$  D T_D  $\alpha_D$   $\iota_D$  F  $\varphi$ 
proof
  show D.isomorphic  $\mathcal{I}_D$  (F  $\mathcal{I}_C$ )
  proof (unfold D.isomorphic-def)
    have « $\mathcal{I}_D : \mathcal{I}_D \rightarrow_D F \mathcal{I}_C$ »  $\wedge$  D.iso  $\mathcal{I}_D$ 
      using strictly-preserves-unity by auto
    thus  $\exists f$ . « $f : \mathcal{I}_D \rightarrow_D F \mathcal{I}_C$ »  $\wedge$  D.iso f by blast
  qed
  fix a b c
  assume a: C.ide a
  assume b: C.ide b
  assume c: C.ide c
  show F a_C[a, b, c]  $\cdot_D$   $\varphi$  (a  $\otimes_C$  b, c)  $\cdot_D$  ( $\varphi$  (a, b)  $\otimes_D$  F c) =
     $\varphi$  (a, b  $\otimes_C$  c)  $\cdot_D$  (F a  $\otimes_D$   $\varphi$  (b, c))  $\cdot_D$  a_D[F a, F b, F c]
    using a b c strictly-preserves-tensor strictly-preserves-assoc
      D.comp-arr-dom D.comp-cod-arr
    by simp
  qed
qed

```

lemma *strict-monoidal-functors-compose*:

```

assumes strict-monoidal-functor B T_B  $\alpha_B$   $\iota_B$  C T_C  $\alpha_C$   $\iota_C$  F
and strict-monoidal-functor C T_C  $\alpha_C$   $\iota_C$  D T_D  $\alpha_D$   $\iota_D$  G

```

```

shows strict-monoidal-functor B TB αB ιB D TD αD ιD (G o F)
proof –
  interpret F: strict-monoidal-functor B TB αB ιB C TC αC ιC F
    using assms(1) by auto
  interpret G: strict-monoidal-functor C TC αC ιC D TD αD ιD G
    using assms(2) by auto
  interpret GoF: composite-functor B C D F G ..
  show ?thesis
    using F.strictly-preserves-T F.strictly-preserves-ι F.strictly-preserves-α
      G.strictly-preserves-T G.strictly-preserves-ι G.strictly-preserves-α
    by (unfold-locales, simp-all)
qed

```

An equivalence of monoidal categories is a monoidal functor whose underlying ordinary functor is also part of an ordinary equivalence of categories.

```

locale equivalence-of-monoidal-categories =
  C: monoidal-category C TC αC ιC +
  D: monoidal-category D TD αD ιD +
  equivalence-of-categories C D F G η ε +
  monoidal-functor D TD αD ιD C TC αC ιC F φ
for C :: 'c comp (infixr ⟨C⟩ 55)
and TC :: 'c * 'c ⇒ 'c
and αC :: 'c * 'c * 'c ⇒ 'c
and ιC :: 'c
and D :: 'd comp (infixr ⟨D⟩ 55)
and TD :: 'd * 'd ⇒ 'd
and αD :: 'd * 'd * 'd ⇒ 'd
and ιD :: 'd
and F :: 'd ⇒ 'c
and φ :: 'd * 'd ⇒ 'c
and ι :: 'c
and G :: 'c ⇒ 'd
and η :: 'd ⇒ 'd
and ε :: 'c ⇒ 'c

```

end

Chapter 4

The Free Monoidal Category

```
theory FreeMonoidalCategory
imports Category3.Subcategory MonoidalFunctor
begin
```

In this theory, we use the monoidal language of a category C defined in *Monoidal-Category.MonoidalCategory* to give a construction of the free monoidal category $\mathcal{F}C$ generated by C . The arrows of $\mathcal{F}C$ are the equivalence classes of formal arrows obtained by declaring two formal arrows to be equivalent if they are parallel and have the same diagonalization. Composition, tensor, and the components of the associator and unitors are all defined in terms of the corresponding syntactic constructs. After defining $\mathcal{F}C$ and showing that it does indeed have the structure of a monoidal category, we prove the freeness: every functor from C to a monoidal category D extends uniquely to a strict monoidal functor from $\mathcal{F}C$ to D .

We then consider the full subcategory $\mathcal{F}_S C$ of $\mathcal{F}C$ whose objects are the equivalence classes of diagonal identity terms (*i.e.* equivalence classes of lists of identity arrows of C), and we show that this category is monoidally equivalent to $\mathcal{F}C$. In addition, we show that $\mathcal{F}_S C$ is the free strict monoidal category, as any functor from C to a strict monoidal category D extends uniquely to a strict monoidal functor from $\mathcal{F}_S C$ to D .

4.1 Syntactic Construction

```
locale free-monoidal-category =
  monoidal-language C
  for C :: 'c comp
begin

  no-notation C.in-hom (‹‹- : - → -››)
  notation C.in-hom (‹‹- : - →C -››)
```

Two terms of the monoidal language of C are defined to be equivalent if they are parallel formal arrows with the same diagonalization.

```
abbreviation equiv
```

where $\text{equiv } t \ u \equiv \text{Par } t \ u \wedge \lfloor t \rfloor = \lfloor u \rfloor$

Arrows of \mathcal{FC} will be the equivalence classes of formal arrows determined by the relation equiv . We define here the property of being an equivalence class of the relation equiv . Later we show that this property coincides with that of being an arrow of the category that we will construct.

type-synonym $'a \ \text{arr} = 'a \ \text{term set}$

definition ARR **where** $\text{ARR } f \equiv f \neq \{\} \wedge (\forall t. t \in f \longrightarrow f = \text{Collect } (\text{equiv } t))$

lemma not-ARR-empty :

shows $\neg \text{ARR } \{\}$

using ARR-def **by** simp

lemma ARR-eqI :

assumes $\text{ARR } f$ **and** $\text{ARR } g$ **and** $f \cap g \neq \{\}$

shows $f = g$

using $\text{assms } \text{ARR-def}$ **by** fastforce

We will need to choose a representative of each equivalence class as a normal form. The requirements we have of these representatives are: (1) the normal form of an arrow t is equivalent to t ; (2) equivalent arrows have identical normal forms; (3) a normal form is a canonical term if and only if its diagonalization is an identity. It follows from these properties and coherence that a term and its normal form have the same evaluation in any monoidal category. We choose here as a normal form for an arrow t the particular term $\text{Inv } (\text{Cod } t \downarrow) \cdot \lfloor t \rfloor \cdot \text{Dom } t \downarrow$. However, the only specific properties of this definition we actually use are the three we have just stated.

definition $\text{norm } (\langle \!| \! \rangle)$

where $\|t\| = \text{Inv } (\text{Cod } t \downarrow) \cdot \lfloor t \rfloor \cdot \text{Dom } t \downarrow$

If t is a formal arrow, then t is equivalent to its normal form.

lemma equiv-norm-Arr :

assumes $\text{Arr } t$

shows $\text{equiv } \|t\| \ t$

proof –

have $\text{Par } t \ (\text{Inv } (\text{Cod } t \downarrow) \cdot \lfloor t \rfloor \cdot \text{Dom } t \downarrow)$

using $\text{assms } \text{Diagonalize-in-Hom } \text{red-in-Hom } \text{Inv-in-Hom } \text{Arr-implies-Ide-Dom}$
 $\text{Arr-implies-Ide-Cod } \text{Ide-implies-Arr } \text{Can-red}$

by auto

moreover have $\lfloor (\text{Inv } (\text{Cod } t \downarrow) \cdot \lfloor t \rfloor \cdot \text{Dom } t \downarrow) \rfloor = \lfloor t \rfloor$

using $\text{assms } \text{Arr-implies-Ide-Dom } \text{Arr-implies-Ide-Cod } \text{Diagonalize-preserves-Ide}$
 $\text{Diagonalize-in-Hom } \text{Diagonalize-Inv } [\text{of } \text{Cod } t \downarrow] \text{Diag-Diagonalize}$
 $\text{CompDiag-Diag-Dom } [\text{of } \lfloor t \rfloor] \text{CompDiag-Cod-Diag } [\text{of } \lfloor t \rfloor]$

by $(\text{simp } \text{add: } \text{Diagonalize-red } [\text{of } \text{Cod } t] \text{Can-red}(1))$

ultimately show $?thesis$ **using** norm-def **by** simp

qed

Equivalent arrows have identical normal forms.

lemma $\text{norm-respects-equiv}$:

assumes *equiv t u*
shows $\|t\| = \|u\|$
using *assms norm-def by simp*

The normal form of an arrow is canonical if and only if its diagonalization is an identity term.

lemma *Can-norm-iff-Ide-Diagonalize*:
assumes *Arr t*
shows $\text{Can } \|t\| \longleftrightarrow \text{Ide } \lfloor t \rfloor$
using *assms norm-def Can-implies-Arr Arr-implies-Ide-Dom Arr-implies-Ide-Cod Can-red Inv-preserves-Can Diagonalize-preserves-Can red-in-Hom Diagonalize-in-Hom Ide-Diagonalize-Can*
by *fastforce*

We now establish various additional properties of normal forms that are consequences of the three already proved. The definition *norm-def* is not used subsequently.

lemma *norm-preserves-Can*:
assumes *Can t*
shows $\text{Can } \|t\|$
using *assms Can-implies-Arr Can-norm-iff-Ide-Diagonalize Ide-Diagonalize-Can by simp*

lemma *Par-Arr-norm*:
assumes *Arr t*
shows $\text{Par } \|t\| \ t$
using *assms equiv-norm-Arr by auto*

lemma *Diagonalize-norm [simp]*:
assumes *Arr t*
shows $\lfloor \|t\| \rfloor = \lfloor t \rfloor$
using *assms equiv-norm-Arr by auto*

lemma *unique-norm*:
assumes *ARR f*
shows $\exists! t. \forall u. u \in f \longrightarrow \|u\| = t$
proof
have $1: (\text{SOME } t. t \in f) \in f$
using *assms ARR-def someI-ex [of $\lambda t. t \in f$] by auto*
show $\bigwedge t. \forall u. u \in f \longrightarrow \|u\| = t \implies t = \|\text{SOME } t. t \in f\|$
using *assms ARR-def 1 by auto*
show $\forall u. u \in f \longrightarrow \|u\| = \|\text{SOME } t. t \in f\|$
using *assms ARR-def 1 norm-respects-equiv by blast*
qed

lemma *Dom-norm*:
assumes *Arr t*
shows $\text{Dom } \|t\| = \text{Dom } t$
using *assms Par-Arr-norm by metis*

lemma *Cod-norm*:

assumes $Arr\ t$
shows $Cod\ ||t|| = Cod\ t$
using *assms Par-Arr-norm* **by** *metis*

lemma *norm-in-Hom*:
assumes $Arr\ t$
shows $||t|| \in Hom\ (Dom\ t)\ (Cod\ t)$
using *assms Par-Arr-norm [of t]* **by** *simp*

As all the elements of an equivalence class have the same normal form, we can use the normal form of an arbitrarily chosen element as a canonical representative.

definition *rep* **where** $rep\ f \equiv ||SOME\ t.\ t \in f||$

lemma *rep-in-ARR*:
assumes $ARR\ f$
shows $rep\ f \in f$
using *assms ARR-def someI-ex [of $\lambda t.\ t \in f$]* *equiv-norm-Arr rep-def ARR-def*
by *fastforce*

lemma *Arr-rep-ARR*:
assumes $ARR\ f$
shows $Arr\ (rep\ f)$
using *assms ARR-def rep-in-ARR* **by** *auto*

We next define a function *mkarr* that maps formal arrows to their equivalence classes. For terms that are not formal arrows, the function yields the empty set.

definition *mkarr* **where** $mkarr\ t = Collect\ (equiv\ t)$

lemma *mkarr-extensionality*:
assumes $\neg Arr\ t$
shows $mkarr\ t = \{\}$
using *assms mkarr-def* **by** *simp*

lemma *ARR-mkarr*:
assumes $Arr\ t$
shows $ARR\ (mkarr\ t)$
using *assms ARR-def mkarr-def* **by** *auto*

lemma *mkarr-memb-ARR*:
assumes $ARR\ f$ **and** $t \in f$
shows $mkarr\ t = f$
using *assms ARR-def mkarr-def* **by** *simp*

lemma *mkarr-rep-ARR [simp]*:
assumes $ARR\ f$
shows $mkarr\ (rep\ f) = f$
using *assms rep-in-ARR mkarr-memb-ARR* **by** *auto*

lemma *Arr-in-mkarr*:

assumes $Arr\ t$
shows $t \in mkarr\ t$
using *assms mkarr-def* **by** *simp*

Two terms are related by *equiv* iff they are both formal arrows and have identical normal forms.

lemma *equiv-iff-eq-norm*:
shows $equiv\ t\ u \iff Arr\ t \wedge Arr\ u \wedge ||t|| = ||u||$
proof
show $equiv\ t\ u \implies Arr\ t \wedge Arr\ u \wedge ||t|| = ||u||$
using *mkarr-def Arr-in-mkarr ARR-mkarr unique-norm* **by** *blast*
show $Arr\ t \wedge Arr\ u \wedge ||t|| = ||u|| \implies equiv\ t\ u$
using *Par-Arr-norm Diagonalize-norm* **by** *metis*
qed

lemma *norm-norm* [*simp*]:
assumes $Arr\ t$
shows $|||t||| = ||t||$
proof –
have $t \in mkarr\ t$
using *assms Arr-in-mkarr* **by** *blast*
moreover have $||t|| \in mkarr\ t$
using *assms equiv-norm-Arr mkarr-def* **by** *simp*
ultimately show *?thesis* **using** *assms ARR-mkarr unique-norm* **by** *auto*
qed

lemma *norm-in-ARR*:
assumes $ARR\ f$ **and** $t \in f$
shows $||t|| \in f$
using *assms ARR-def equiv-iff-eq-norm norm-norm Par-Arr-norm* **by** *fastforce*

lemma *norm-rep-ARR* [*simp*]:
assumes $ARR\ f$
shows $||rep\ f|| = rep\ f$
using *assms ARR-def someI-ex* [of $\lambda t. t \in f$] *rep-def norm-norm* **by** *fastforce*

lemma *norm-memb-eq-rep-ARR*:
assumes $ARR\ f$ **and** $t \in f$
shows $norm\ t = rep\ f$
using *assms ARR-def someI-ex* [of $\lambda t. t \in f$] *unique-norm rep-def* **by** *metis*

lemma *rep-mkarr*:
assumes $Arr\ f$
shows $rep\ (mkarr\ f) = ||f||$
using *assms ARR-mkarr Arr-in-mkarr norm-memb-eq-rep-ARR* **by** *fastforce*

To prove that two terms determine the same equivalence class, it suffices to show that they are parallel formal arrows with identical diagonalizations.

lemma *mkarr-eqI* [*intro*]:

assumes $Par\ f\ g$ **and** $\lfloor f \rfloor = \lfloor g \rfloor$
shows $mkarr\ f = mkarr\ g$
using *assms* **by** (*metis* *ARR-mkarr-equiv-iff-eq-norm* *rep-mkarr* *mkarr-rep-ARR*)

We use canonical representatives to lift the formal domain and codomain functions from terms to equivalence classes.

abbreviation DOM **where** $DOM\ f \equiv Dom\ (rep\ f)$
abbreviation COD **where** $COD\ f \equiv Cod\ (rep\ f)$

lemma *DOM-mkarr*:
assumes $Arr\ t$
shows $DOM\ (mkarr\ t) = Dom\ t$
using *assms* *rep-mkarr* **by** (*metis* *Par-Arr-norm*)

lemma *COD-mkarr*:
assumes $Arr\ t$
shows $COD\ (mkarr\ t) = Cod\ t$
using *assms* *rep-mkarr* **by** (*metis* *Par-Arr-norm*)

A composition operation can now be defined on equivalence classes using the syntactic constructor *Comp*.

definition *comp* (**infixr** $\langle \cdot \rangle$ 55)
where $comp\ f\ g \equiv (if\ ARR\ f \wedge ARR\ g \wedge DOM\ f = COD\ g$
 $then\ mkarr\ ((rep\ f) \cdot (rep\ g))\ else\ \{\})$

We commence the task of showing that the composition *comp* so defined determines a category.

interpretation *partial-composition* *comp*
apply *unfold-locales*
using *comp-def* *not-ARR-empty* **by** *metis*

notation *in-hom* ($\langle \langle - : - \rightarrow - \rangle \rangle$)

The empty set serves as the null for the composition.

lemma *null-char*:
shows $null = \{\}$
proof –
let $?P = \lambda n. \forall f. f \cdot n = n \wedge n \cdot f = n$
have $?P\ \{\}$ **using** *comp-def* *not-ARR-empty* **by** *simp*
moreover **have** $\exists! n. ?P\ n$ **using** *ex-un-null* **by** *metis*
ultimately **show** *?thesis* **using** *null-def* *theI-unique* [*of* $?P\ \{\}$]
by (*metis* *null-is-zero*(2))
qed

lemma *ARR-comp*:
assumes $ARR\ f$ **and** $ARR\ g$ **and** $DOM\ f = COD\ g$
shows $ARR\ (f \cdot g)$
using *assms* *comp-def* *Arr-rep-ARR* *ARR-mkarr*(1) **by** *simp*

lemma *DOM-comp* [*simp*]:
assumes *ARR f and ARR g and DOM f = COD g*
shows $DOM (f \cdot g) = DOM g$
using *assms comp-def ARR-comp Arr-rep-ARR DOM-mkarr by simp*

lemma *COD-comp* [*simp*]:
assumes *ARR f and ARR g and DOM f = COD g*
shows $COD (f \cdot g) = COD f$
using *assms comp-def ARR-comp Arr-rep-ARR COD-mkarr by simp*

lemma *comp-assoc*:
assumes $g \cdot f \neq null$ **and** $h \cdot g \neq null$
shows $h \cdot (g \cdot f) = (h \cdot g) \cdot f$
proof –
have 1: $ARR f \wedge ARR g \wedge ARR h \wedge DOM h = COD g \wedge DOM g = COD f$
using *assms comp-def not-ARR-empty null-char by metis*
hence 2: $Arr (rep f) \wedge Arr (rep g) \wedge Arr (rep h) \wedge$
 $Dom (rep h) = Cod (rep g) \wedge Dom (rep g) = Cod (rep f)$
using *Arr-rep-ARR by simp*
have 3: $h \cdot g \cdot f = mkarr (rep h \cdot rep (mkarr (rep g \cdot rep f)))$
using 1 2 3 *comp-def ARR-comp COD-comp by simp*
also have ... = $mkarr (rep h \cdot rep g \cdot rep f)$
proof –
have *equiv* $(rep h \cdot rep (mkarr (rep g \cdot rep f))) (rep h \cdot rep g \cdot rep f)$
proof –
have *Par* $(rep h \cdot rep (mkarr (rep g \cdot rep f))) (rep h \cdot rep g \cdot rep f)$
using 1 2 3 *DOM-mkarr ARR-comp COD-comp mkarr-extensionality not-ARR-empty*
by (*metis Arr.simps(4) Cod.simps(4) Dom.simps(4) snd-map-prod*)

moreover have $\lfloor rep h \cdot rep (mkarr (rep g \cdot rep f)) \rfloor = \lfloor rep h \cdot rep g \cdot rep f \rfloor$
using 1 2 *Arr-rep-ARR rep-mkarr rep-in-ARR assms(1) ARR-comp mkarr-extensionality*
 $comp-def equiv-iff-eq-norm norm-memb-eq-rep-ARR null-char$
by *auto*
ultimately show *?thesis using equiv-iff-eq-norm by blast*
qed
thus *?thesis*
using *mkarr-def by force*
qed
also have ... = $mkarr ((rep h \cdot rep g) \cdot rep f)$
proof –
have *Par* $(rep h \cdot rep g \cdot rep f) ((rep h \cdot rep g) \cdot rep f)$
using 2 *by simp*
moreover have $\lfloor rep h \cdot rep g \cdot rep f \rfloor = \lfloor (rep h \cdot rep g) \cdot rep f \rfloor$
using 2 *Diag-Diagonalize by (simp add: CompDiag-assoc)*
ultimately show *?thesis*
using *equiv-iff-eq-norm by (simp add: mkarr-def)*
qed
also have ... = $mkarr (rep (mkarr (rep h \cdot rep g)) \cdot rep f)$
proof –

```

have equiv (rep (mkarr (rep h · rep g)) · rep f) ((rep h · rep g) · rep f)
proof –
  have Par (rep (mkarr (rep h · rep g)) · rep f) ((rep h · rep g) · rep f)
    using 1 2 Arr-rep-ARR DOM-comp ARR-comp COD-comp comp-def by auto
  moreover have [rep (mkarr (rep h · rep g)) · rep f] = [(rep h · rep g) · rep f]
  using assms(2) 1 2 ARR-comp Arr-rep-ARR mkarr-extensionality rep-mkarr rep-in-ARR
    equiv-iff-eq-norm norm-memb-eq-rep-ARR comp-def null-char
  by simp
  ultimately show ?thesis using equiv-iff-eq-norm by blast
qed
thus ?thesis
  using mkarr-def by auto
qed
also have ... = (h · g) · f
  using 1 comp-def ARR-comp DOM-comp by simp
finally show ?thesis by blast
qed

```

lemma *Comp-in-comp-ARR*:

assumes *ARR f* **and** *ARR g* **and** $DOM f = COD g$

and $t \in f$ **and** $u \in g$

shows $t \cdot u \in f \cdot g$

proof –

have equiv (t · u) (rep f · rep g)

proof –

have 1: Par (t · u) (rep f · rep g)

using assms ARR-def Arr-rep-ARR COD-mkarr DOM-mkarr mkarr-memb-ARR
mkarr-extensionality

by (metis (no-types, lifting) Arr.simps(4) Cod.simps(4) Dom.simps(4) snd-map-prod)

moreover **have** [t · u] = [rep f · rep g]

using assms 1 rep-in-ARR equiv-iff-eq-norm norm-memb-eq-rep-ARR

by (metis (no-types, lifting) Arr.simps(4) Diagonalize.simps(4))

ultimately **show** ?thesis **by** simp

qed

thus ?thesis

using assms comp-def mkarr-def **by** simp

qed

Ultimately, we will show that that the identities of the category are those equivalence classes, all of whose members diagonalize to formal identity arrows, having the further property that their canonical representative is a formal endo-arrow.

definition *IDE* **where** $IDE f \equiv ARR f \wedge (\forall t. t \in f \longrightarrow Ide [t]) \wedge DOM f = COD f$

lemma *IDE-implies-ARR*:

assumes *IDE f*

shows *ARR f*

using assms IDE-def ARR-def **by** auto

lemma *IDE-mkarr-Ide*:
assumes *Ide a*
shows *IDE (mkarr a)*
proof –
 have *DOM (mkarr a) = COD (mkarr a)*
 using *assms mkarr-def equiv-iff-eq-norm Par-Arr-norm COD-mkarr DOM-mkarr Ide-in-Hom*
 by (*metis Ide-implies-Can Inv-Ide Ide-implies-Arr Inv-preserves-Can(2)*)
 moreover have *ARR (mkarr a) \wedge ($\forall t. t \in \text{mkarr } a \longrightarrow \text{Ide } [t]$)*
 proof –
 have *ARR (mkarr a)* **using** *assms ARR-mkarr Ide-implies-Arr* **by** *simp*
 moreover have $\forall t. t \in \text{mkarr } a \longrightarrow \text{Ide } [t]$
 using *assms mkarr-def Diagonalize-preserves-Ide* **by** *fastforce*
 ultimately show *?thesis* **by** *blast*
 qed
 ultimately show *?thesis* **using** *IDE-def* **by** *blast*
qed

lemma *IDE-implies-ide*:
assumes *IDE a*
shows *ide a*
proof (*unfold ide-def*)
 have *a · a \neq null*
 proof –
 have *rep a · rep a \in a · a*
 using *assms IDE-def comp-def Arr-rep-ARR Arr-in-mkarr* **by** *simp*
 thus *?thesis*
 using *null-char* **by** *auto*
 qed
 moreover have $\bigwedge f. (f \cdot a \neq \text{null} \longrightarrow f \cdot a = f) \wedge (a \cdot f \neq \text{null} \longrightarrow a \cdot f = f)$
 proof
 fix *f :: 'c arr*
 show *a · f \neq null \longrightarrow a · f = f*
 proof
 assume *f: a · f \neq null*
 hence *ARR f*
 using *comp-def null-char* **by** *auto*
 have *rep a · rep f \in a · f*
 using *assms f Comp-in-comp-ARR comp-def rep-in-ARR null-char* **by** *metis*
 moreover have *rep a · rep f \in f*
 proof –
 have *rep f \in f*
 using $\langle \text{ARR } f \rangle$ *rep-in-ARR* **by** *auto*
 moreover have *equiv (rep a · rep f) (rep f)*
 proof –
 have *1: Par (rep a · rep f) (rep f)*
 using *assms f comp-def mkarr-extensionality Arr-rep-ARR IDE-def null-char*
 by (*metis Cod.simps(4) Dom.simps(4)*)
 moreover have $[rep a \cdot rep f] = [rep f]$
 using *assms f 1 comp-def IDE-def CompDiag-Ide-Diag Diag-Diagonalize(1)*
 qed
 qed
 qed

```

      Diag-Diagonalize(2) Diag-Diagonalize(3) rep-in-ARR
    by auto
    ultimately show ?thesis by auto
  qed
  ultimately show ?thesis
    using  $\langle ARR\ f \rangle$  ARR-def by auto
  qed
  ultimately show  $a \cdot f = f$ 
    using mkarr-memb-ARR comp-def by auto
  qed
  show  $f \cdot a \neq null \longrightarrow f \cdot a = f$ 
  proof
    assume  $f: f \cdot a \neq null$ 
    hence ARR f
      using comp-def null-char by auto
    have  $rep\ f \cdot rep\ a \in f \cdot a$ 
      using assms f Comp-in-comp-ARR comp-def rep-in-ARR null-char by metis
    moreover have  $rep\ f \cdot rep\ a \in f$ 
    proof -
      have  $rep\ f \in f$ 
        using  $\langle ARR\ f \rangle$  rep-in-ARR by auto
      moreover have equiv  $(rep\ f \cdot rep\ a)$   $(rep\ f)$ 
    proof -
      have  $1: Par\ (rep\ f \cdot rep\ a)\ (rep\ f)$ 
        using assms f comp-def mkarr-extensionality Arr-rep-ARR IDE-def null-char
        by  $(metis\ Cod.simps(4)\ Dom.simps(4))$ 
      moreover have  $\lfloor rep\ f \cdot rep\ a \rfloor = \lfloor rep\ f \rfloor$ 
        using assms f 1 comp-def IDE-def CompDiag-Diag-Ide
          Diag-Diagonalize(1) Diag-Diagonalize(2) Diag-Diagonalize(3)
          rep-in-ARR
      by force
    ultimately show ?thesis by auto
  qed
  ultimately show ?thesis
    using  $\langle ARR\ f \rangle$  ARR-def by auto
  qed
  ultimately show  $f \cdot a = f$ 
    using mkarr-memb-ARR comp-def by auto
  qed
  qed
  ultimately show  $a \cdot a \neq null \wedge$ 
     $(\forall f. (f \cdot a \neq null \longrightarrow f \cdot a = f) \wedge (a \cdot f \neq null \longrightarrow a \cdot f = f))$ 
  by blast
  qed

lemma ARR-iff-has-domain:
shows  $ARR\ f \longleftrightarrow domains\ f \neq \{\}$ 
proof
  assume  $f: domains\ f \neq \{\}$ 

```

show $ARR\ f$ **using** f *domains-def comp-def null-char* **by** *auto*
next
assume $f: ARR\ f$
have $Ide\ (DOM\ f)$
using f *ARR-def* **by** (*simp add: Arr-implies-Ide-Dom Arr-rep-ARR*)
hence $IDE\ (mkarr\ (DOM\ f))$ **using** *IDE-mkarr-Ide* **by** *metis*
hence $ide\ (mkarr\ (DOM\ f))$ **using** *IDE-implies-ide* **by** *simp*
moreover **have** $f \cdot mkarr\ (DOM\ f) = f$
proof –
have $1: rep\ f \cdot DOM\ f \in f \cdot mkarr\ (DOM\ f)$
using f *Comp-in-comp-ARR*
using *IDE-implies-ARR Ide-in-Hom rep-in-ARR* $\langle IDE\ (mkarr\ (DOM\ f)) \rangle$
 $\langle Ide\ (DOM\ f) \rangle$ *Arr-in-mkarr COD-mkarr*
by *fastforce*
moreover **have** $rep\ f \cdot DOM\ f \in f$
proof –
have $2: rep\ f \in f$ **using** f *rep-in-ARR* **by** *simp*
moreover **have** *equiv* ($rep\ f \cdot DOM\ f$) ($rep\ f$)
by (*metis 1 Arr.simps(4) Arr-rep-ARR COD-mkarr Cod.simps(4)*
Diagonalize-Comp-Arr-Dom Dom.simps(4) IDE-def Ide-implies-Arr
 $\langle IDE\ (mkarr\ (DOM\ f)) \rangle$ $\langle Ide\ (DOM\ f) \rangle$ *all-not-in-conv DOM-mkarr comp-def*)
ultimately **show** *?thesis*
using f *ARR-eqI 1* $\langle ide\ (mkarr\ (DOM\ f)) \rangle$ *null-char ide-def* **by** *auto*
qed
ultimately **show** *?thesis*
using f *ARR-eqI* $\langle ide\ (mkarr\ (DOM\ f)) \rangle$ *null-char ide-def* **by** *auto*
qed
ultimately **show** $domains\ f \neq \{\}$
using f *domains-def not-ARR-empty null-char* **by** *auto*
qed

lemma *ARR-iff-has-codomain:*

shows $ARR\ f \iff codomains\ f \neq \{\}$

proof

assume $f: codomains\ f \neq \{\}$

show $ARR\ f$ **using** f *codomains-def comp-def null-char* **by** *auto*

next

assume $f: ARR\ f$

have $Ide\ (COD\ f)$

using f *ARR-def* **by** (*simp add: Arr-rep-ARR Arr-implies-Ide-Cod*)

hence $IDE\ (mkarr\ (COD\ f))$ **using** *IDE-mkarr-Ide* **by** *metis*

hence $ide\ (mkarr\ (COD\ f))$ **using** *IDE-implies-ide* **by** *simp*

moreover **have** $mkarr\ (COD\ f) \cdot f = f$

proof –

have $1: COD\ f \cdot rep\ f \in mkarr\ (COD\ f) \cdot f$

using f *Comp-in-comp-ARR*

using *IDE-implies-ARR Ide-in-Hom rep-in-ARR* $\langle IDE\ (mkarr\ (COD\ f)) \rangle$

$\langle Ide\ (COD\ f) \rangle$ *Arr-in-mkarr DOM-mkarr*

by *fastforce*

```

moreover have  $COD f \cdot rep f \in f$ 
  using 1 null-char norm-rep-ARR norm-memb-eq-rep-ARR mkarr-memb-ARR
     $\langle ide (mkarr (COD f)) \rangle emptyE equiv-iff-eq-norm mkarr-extensionality ide-def$ 
  by metis
ultimately show ?thesis
  using f ARR-eqI  $\langle ide (mkarr (COD f)) \rangle null-char ide-def$  by auto
qed
ultimately show  $codomains f \neq \{\}$ 
  using codomains-def f not-ARR-empty null-char by auto
qed

```

```

lemma arr-iff-ARR:
shows  $arr f \longleftrightarrow ARR f$ 
  using arr-def ARR-iff-has-domain ARR-iff-has-codomain by simp

```

The arrows of the category are the equivalence classes of formal arrows.

```

lemma arr-char:
shows  $arr f \longleftrightarrow f \neq \{\} \wedge (\forall t. t \in f \longrightarrow f = mkarr t)$ 
  using arr-iff-ARR ARR-def mkarr-def by simp

```

```

lemma seq-char:
shows  $seq g f \longleftrightarrow g \cdot f \neq null$ 
proof
  show  $g \cdot f \neq null \implies seq g f$ 
    using comp-def null-char Comp-in-comp-ARR rep-in-ARR ARR-mkarr
      Arr-rep-ARR arr-iff-ARR
    by auto
  show  $seq g f \implies g \cdot f \neq null$ 
    by auto
qed

```

```

lemma seq-char':
shows  $seq g f \longleftrightarrow ARR f \wedge ARR g \wedge DOM g = COD f$ 
proof
  show  $ARR f \wedge ARR g \wedge DOM g = COD f \implies seq g f$ 
    using comp-def null-char Comp-in-comp-ARR rep-in-ARR ARR-mkarr
      Arr-rep-ARR arr-iff-ARR
    by auto
  have  $\neg (ARR f \wedge ARR g \wedge DOM g = COD f) \implies g \cdot f = null$ 
    using comp-def null-char by auto
  thus  $seq g f \implies ARR f \wedge ARR g \wedge DOM g = COD f$ 
    using ext by fastforce
qed

```

Finally, we can show that the composition *comp* determines a category.

```

interpretation category comp
proof
  show  $\bigwedge f. domains f \neq \{\} \longleftrightarrow codomains f \neq \{\}$ 
    using ARR-iff-has-domain ARR-iff-has-codomain by simp

```

```

show 1:  $\bigwedge f g. g \cdot f \neq \text{null} \implies \text{seq } g f$ 
  using comp-def ARR-comp null-char arr-iff-ARR by metis
fix f g h
show  $\text{seq } h g \implies \text{seq } (h \cdot g) f \implies \text{seq } g f$ 
  using seq-char' by auto
show  $\text{seq } h (g \cdot f) \implies \text{seq } g f \implies \text{seq } h g$ 
  using seq-char' by auto
show  $\text{seq } g f \implies \text{seq } h g \implies \text{seq } (h \cdot g) f$ 
  using seq-char' ARR-comp arr-iff-ARR by auto
show  $\text{seq } g f \implies \text{seq } h g \implies (h \cdot g) \cdot f = h \cdot g \cdot f$ 
  using seq-char comp-assoc by auto
qed

```

```

lemma mkarr-rep [simp]:
assumes arr f
shows  $\text{mkarr } (\text{rep } f) = f$ 
  using assms arr-iff-ARR by simp

```

```

lemma arr-mkarr [simp]:
assumes Arr t
shows  $\text{arr } (\text{mkarr } t)$ 
  using assms by (simp add: ARR-mkarr arr-iff-ARR)

```

```

lemma mkarr-memb:
assumes  $t \in f$  and arr f
shows  $\text{Arr } t$  and  $\text{mkarr } t = f$ 
  using assms arr-char mkarr-extensionality by auto

```

```

lemma rep-in-arr [simp]:
assumes arr f
shows  $\text{rep } f \in f$ 
  using assms by (simp add: rep-in-ARR arr-iff-ARR)

```

```

lemma Arr-rep [simp]:
assumes arr f
shows  $\text{Arr } (\text{rep } f)$ 
  using assms mkarr-memb rep-in-arr by blast

```

```

lemma rep-in-Hom:
assumes arr f
shows  $\text{rep } f \in \text{Hom } (\text{DOM } f) (\text{COD } f)$ 
  using assms by simp

```

```

lemma norm-memb-eq-rep:
assumes arr f and  $t \in f$ 
shows  $\|t\| = \text{rep } f$ 
  using assms arr-iff-ARR norm-memb-eq-rep-ARR by auto

```

```

lemma norm-rep:

```


assumes $arr\ f$
shows $\|rep\ f\| = rep\ f$
using $assms\ norm-memb-eq-rep$ **by** $simp$

Composition, domain, and codomain on arrows reduce to the corresponding syntactic operations on their representative terms.

lemma $comp-mkarr$ [$simp$]:
assumes $Arr\ t$ **and** $Arr\ u$ **and** $Dom\ t = Cod\ u$
shows $mkarr\ t \cdot mkarr\ u = mkarr\ (t \cdot u)$
using $assms$
by ($metis$ ($no-types$, $lifting$) $ARR-mkarr\ ARR-comp\ ARR-def\ Arr-in-mkarr\ COD-mkarr\ Comp-in-comp-ARR\ DOM-mkarr\ mkarr-def$)

lemma $dom-char$:
shows $dom\ f = (if\ arr\ f\ then\ mkarr\ (DOM\ f)\ else\ null)$
proof –
have $\neg arr\ f \implies ?thesis$
using $dom-def$ **by** ($simp\ add: arr-def$)
moreover **have** $arr\ f \implies ?thesis$
proof –
assume $f: arr\ f$
have $dom\ f = mkarr\ (DOM\ f)$
proof ($intro\ dom-eqI$)
have $1: Ide\ (DOM\ f)$
using $f\ arr-char$ **by** ($metis\ Arr-rep\ Arr-implies-Ide-Dom$)
hence $2: IDE\ (mkarr\ (DOM\ f))$
using $IDE-mkarr-Ide$ **by** $metis$
thus $ide\ (mkarr\ (DOM\ f))$ **using** $IDE-implies-ide$ **by** $simp$
moreover **show** $seq\ f\ (mkarr\ (DOM\ f))$
proof –
have $f \cdot mkarr\ (DOM\ f) \neq null$
using $f\ 1\ 2\ ARR-def\ DOM-mkarr\ IDE-implies-ARR\ Ide-in-Hom\ ARR-comp\ IDE-def\ ARR-iff-has-codomain\ ARR-iff-has-domain\ null-char\ arr-def$
by ($metis$ ($mono-tags$, $lifting$) $mem-Collect-eq$)
thus $?thesis$ **using** $seq-char$ **by** $simp$
qed
qed
thus $?thesis$ **using** f **by** $simp$
qed
ultimately **show** $?thesis$ **by** $blast$
qed

lemma $dom-simp$:
assumes $arr\ f$
shows $dom\ f = mkarr\ (DOM\ f)$
using $assms\ dom-char$ **by** $simp$

lemma $cod-char$:
shows $cod\ f = (if\ arr\ f\ then\ mkarr\ (COD\ f)\ else\ null)$

```

proof –
  have  $\neg \text{arr } f \implies ?thesis$ 
    using cod-def by (simp add: arr-def)
  moreover have  $\text{arr } f \implies ?thesis$ 
  proof –
    assume  $f: \text{arr } f$ 
    have  $\text{cod } f = \text{mkarr } (\text{COD } f)$ 
    proof (intro cod-eqI)
      have  $1: \text{Ide } (\text{COD } f)$ 
        using  $f$  arr-char by (metis Arr-rep Arr-implies-Ide-Cod)
      hence  $2: \text{IDE } (\text{mkarr } (\text{COD } f))$ 
        using IDE-mkarr-Ide by metis
      thus  $\text{ide } (\text{mkarr } (\text{COD } f))$  using IDE-implies-ide by simp
      moreover show  $\text{seq } (\text{mkarr } (\text{COD } f)) \ f$ 
      proof –
        have  $\text{mkarr } (\text{COD } f) \cdot f \neq \text{null}$ 
          using  $f$   $1$   $2$  ARR-def DOM-mkarr IDE-implies-ARR Ide-in-Hom ARR-comp IDE-def
            ARR-iff-has-codomain ARR-iff-has-domain null-char arr-def
          by (metis (mono-tags, lifting) mem-Collect-eq)
        thus  $?thesis$  using seq-char by simp
      qed
    qed
  thus  $?thesis$  using  $f$  by simp
qed
ultimately show  $?thesis$  by blast
qed

```

```

lemma cod-simp:
assumes  $\text{arr } f$ 
shows  $\text{cod } f = \text{mkarr } (\text{COD } f)$ 
  using assms cod-char by simp

```

```

lemma Dom-memb:
assumes  $\text{arr } f$  and  $t \in f$ 
shows  $\text{Dom } t = \text{DOM } f$ 
  using assms DOM-mkarr mkarr-extensionality arr-char by fastforce

```

```

lemma Cod-memb:
assumes  $\text{arr } f$  and  $t \in f$ 
shows  $\text{Cod } t = \text{COD } f$ 
  using assms COD-mkarr mkarr-extensionality arr-char by fastforce

```

```

lemma dom-mkarr [simp]:
assumes  $\text{Arr } t$ 
shows  $\text{dom } (\text{mkarr } t) = \text{mkarr } (\text{Dom } t)$ 
  using assms dom-char DOM-mkarr arr-mkarr by auto

```

```

lemma cod-mkarr [simp]:
assumes  $\text{Arr } t$ 

```

shows $\text{cod } (mkarr\ t) = mkarr\ (\text{Cod } t)$
using *assms cod-char COD-mkarr arr-mkarr* **by** *auto*

lemma *mkarr-in-hom*:
assumes *Arr t*
shows $\langle mkarr\ t : mkarr\ (\text{Dom } t) \rightarrow mkarr\ (\text{Cod } t) \rangle$
using *assms arr-mkarr dom-mkarr cod-mkarr* **by** *auto*

lemma *DOM-in-dom* [*intro*]:
assumes *arr f*
shows $\text{DOM } f \in \text{dom } f$
using *assms dom-char*
by (*metis Arr-in-mkarr mkarr-extensionality ideD(1) ide-dom not-arr-null null-char*)

lemma *COD-in-cod* [*intro*]:
assumes *arr f*
shows $\text{COD } f \in \text{cod } f$
using *assms cod-char*
by (*metis Arr-in-mkarr mkarr-extensionality ideD(1) ide-cod not-arr-null null-char*)

lemma *DOM-dom*:
assumes *arr f*
shows $\text{DOM } (\text{dom } f) = \text{DOM } f$
using *assms Arr-rep Arr-implies-Ide-Dom Ide-implies-Arr dom-char rep-mkarr Par-Arr-norm*
Ide-in-Hom
by *simp*

lemma *DOM-cod*:
assumes *arr f*
shows $\text{DOM } (\text{cod } f) = \text{COD } f$
using *assms Arr-rep Arr-implies-Ide-Cod Ide-implies-Arr cod-char rep-mkarr Par-Arr-norm*
Ide-in-Hom
by *simp*

lemma *memb-equiv*:
assumes *arr f* **and** $t \in f$ **and** $u \in f$
shows $\text{Par } t\ u$ **and** $\lfloor t \rfloor = \lfloor u \rfloor$
proof –
show $\text{Par } t\ u$
using *assms Cod-memb Dom-memb mkarr-memb(1)* **by** *metis*
show $\lfloor t \rfloor = \lfloor u \rfloor$
using *assms arr-iff-ARR ARR-def* **by** *auto*
qed

Two arrows can be proved equal by showing that they are parallel and have representatives with identical diagonalizations.

lemma *arr-eqI*:
assumes *par f g* **and** $t \in f$ **and** $u \in g$ **and** $\lfloor t \rfloor = \lfloor u \rfloor$
shows $f = g$

proof –
have $Arr\ t \wedge Arr\ u$ **using** *assms mkarr-memb(1)* **by** *blast*
moreover have $Dom\ t = Dom\ u \wedge Cod\ t = Cod\ u$
using *assms Dom-memb Cod-memb comp-def arr-char comp-arr-dom comp-cod-arr*
by *(metis (full-types))*
ultimately have $Par\ t\ u$ **by** *simp*
thus *?thesis*
using *assms arr-char* **by** *(metis rep-mkarr rep-in-arr equiv-iff-eq-norm)*
qed

lemma *comp-char*:
shows $f \cdot g = (if\ seq\ f\ g\ then\ mkarr\ (rep\ f \cdot rep\ g)\ else\ null)$
using *comp-def seq-char arr-char* **by** *meson*

The mapping that takes identity terms to their equivalence classes is injective.

lemma *mkarr-inj-on-Ide*:
assumes $Ide\ t$ **and** $Ide\ u$ **and** $mkarr\ t = mkarr\ u$
shows $t = u$
using *assms*
by *(metis (mono-tags, lifting) COD-mkarr Ide-in-Hom mem-Collect-eq)*

lemma *Comp-in-comp* [*intro*]:
assumes $arr\ f$ **and** $g \in hom\ (dom\ g)\ (dom\ f)$ **and** $t \in f$ **and** $u \in g$
shows $t \cdot u \in f \cdot g$
proof –
have $ARR\ f$ **using** *assms arr-iff-ARR* **by** *simp*
moreover have $ARR\ g$ **using** *assms arr-iff-ARR* **by** *auto*
moreover have $DOM\ f = COD\ g$
using *assms dom-char cod-char mkarr-inj-on-Ide Arr-implies-Ide-Cod Arr-implies-Ide-Dom*
by *force*
ultimately show *?thesis* **using** *assms Comp-in-comp-ARR* **by** *simp*
qed

An arrow is defined to be “canonical” if some (equivalently, all) its representatives diagonalize to an identity term.

definition *can*
where $can\ f \equiv arr\ f \wedge (\exists t. t \in f \wedge Ide\ [t])$

lemma *can-def-alt*:
shows $can\ f \iff arr\ f \wedge (\forall t. t \in f \longrightarrow Ide\ [t])$
proof
assume $arr\ f \wedge (\forall t. t \in f \longrightarrow Ide\ [t])$
thus $can\ f$ **using** *can-def arr-char* **by** *fastforce*
next
assume $f: can\ f$
show $arr\ f \wedge (\forall t. t \in f \longrightarrow Ide\ [t])$
proof –
obtain t **where** $t: t \in f \wedge Ide\ [t]$ **using** $f\ can-def$ **by** *auto*
have $ARR\ f$ **using** $f\ can-def\ arr-char\ ARR-def\ mkarr-def$ **by** *simp*

hence $\forall u. u \in f \longrightarrow \|u\| = \|t\|$ **using** *t unique-norm* **by** *auto*
hence $\forall u. u \in f \longrightarrow \lfloor t \rfloor = \lfloor u \rfloor$
using *t* **by** (*metis* $\langle ARR\ f \rangle$ *equiv-iff-eq-norm arr-iff-ARR mkarr-memb(1)*)
hence $\forall u. u \in f \longrightarrow Ide\ \lfloor u \rfloor$
using *t* **by** *metis*
thus *?thesis* **using** *f can-def* **by** *blast*
qed
qed

lemma *can-implies-arr*:
assumes *can f*
shows *arr f*
using *assms can-def* **by** *auto*

The identities of the category are precisely the canonical endo-arrows.

lemma *ide-char*:
shows $ide\ f \longleftrightarrow can\ f \wedge dom\ f = cod\ f$
proof
assume *f: ide f*
show $can\ f \wedge dom\ f = cod\ f$
using *f can-def arr-char dom-char cod-char IDE-def Arr-implies-Ide-Cod can-def-alt*
Arr-rep IDE-mkarr-Ide
by (*metis ideD(1) ideD(3)*)
next
assume *f: can f \wedge dom f = cod f*
show *ide f*
proof –
have $f = dom\ f$
proof (*intro arr-eqI*)
show $par\ f\ (dom\ f)$ **using** *f can-def* **by** *simp*
show $rep\ f \in f$ **using** *f can-def* **by** *simp*
show $DOM\ f \in dom\ f$ **using** *f can-def* **by** *auto*
show $\lfloor rep\ f \rfloor = \lfloor DOM\ f \rfloor$
proof –
have $\lfloor rep\ f \rfloor \in Hom\ \lfloor DOM\ f \rfloor\ \lfloor COD\ f \rfloor$
using *f can-def Diagonalize-in-Hom* **by** *simp*
moreover **have** $Ide\ \lfloor rep\ f \rfloor$ **using** *f can-def-alt rep-in-arr* **by** *simp*
ultimately **show** *?thesis*
using *f can-def Ide-in-Hom* **by** *simp*
qed
qed
thus *?thesis* **using** *f can-implies-arr ide-dom [of f]* **by** *auto*
qed
qed

lemma *ide-iff-IDE*:
shows $ide\ a \longleftrightarrow IDE\ a$
using *ide-char IDE-def can-def-alt arr-iff-ARR dom-char cod-char mkarr-inj-on-Ide*
Arr-implies-Ide-Cod Arr-implies-Ide-Dom Arr-rep

by auto

lemma *ide-mkarr-Ide*:

assumes *Ide a*

shows *ide (mkarr a)*

using *assms IDE-mkarr-Ide ide-iff-IDE* **by simp**

lemma *rep-dom*:

assumes *arr f*

shows *rep (dom f) = ||DOM f||*

using *assms dom-simp rep-mkarr Arr-rep Arr-implies-Ide-Dom* **by simp**

lemma *rep-cod*:

assumes *arr f*

shows *rep (cod f) = ||COD f||*

using *assms cod-simp rep-mkarr Arr-rep Arr-implies-Ide-Cod* **by simp**

lemma *rep-preserves-seq*:

assumes *seq g f*

shows *Seq (rep g) (rep f)*

using *assms Arr-rep dom-char cod-char mkarr-inj-on-Ide Arr-implies-Ide-Dom
Arr-implies-Ide-Cod*

by auto

lemma *rep-comp*:

assumes *seq g f*

shows *rep (g · f) = ||rep g · rep f||*

proof –

have *rep (g · f) = rep (mkarr (rep g · rep f))*

using *assms comp-char* **by metis**

also have *... = ||rep g · rep f||*

using *assms rep-preserves-seq rep-mkarr* **by simp**

finally show *?thesis* **by blast**

qed

The equivalence classes of canonical terms are canonical arrows.

lemma *can-mkarr-Can*:

assumes *Can t*

shows *can (mkarr t)*

using *assms Arr-in-mkarr Can-implies-Arr Ide-Diagonalize-Can arr-mkarr can-def* **by blast**

lemma *ide-implies-can*:

assumes *ide a*

shows *can a*

using *assms ide-char* **by blast**

lemma *Can-rep-can*:

assumes *can f*

shows *Can (rep f)*

proof –
have $Can \parallel rep f \parallel$
using *assms can-def-alt Can-norm-iff-Ide-Diagonalize* **by** *auto*
moreover **have** $rep f = \parallel rep f \parallel$
using *assms can-implies-arr norm-rep* **by** *simp*
ultimately show *?thesis* **by** *simp*
qed

Parallel canonical arrows are identical.

lemma *can-coherence*:
assumes *par f g* **and** *can f* **and** *can g*
shows $f = g$
proof –
have $\lfloor rep f \rfloor = \lfloor rep g \rfloor$
proof –
have $\lfloor rep f \rfloor = \lfloor DOM f \rfloor$
using *assms Ide-Diagonalize-Can Can-rep-can Diagonalize-in-Hom Ide-in-Hom* **by** *force*
also **have** $\dots = \lfloor DOM g \rfloor$
using *assms dom-char equiv-iff-eq-norm*
by (*metis DOM-in-dom mkarr-memb(1) rep-mkarr arr-dom-iff-arr*)
also **have** $\dots = \lfloor rep g \rfloor$
using *assms Ide-Diagonalize-Can Can-rep-can Diagonalize-in-Hom Ide-in-Hom* **by** *force*
finally show *?thesis* **by** *blast*
qed
hence $rep f = rep g$
using *assms rep-in-arr norm-memb-eq-rep equiv-iff-eq-norm*
by (*metis (no-types, lifting) arr-eqI*)
thus *?thesis*
using *assms arr-eqI [of f g] rep-in-arr [of f] rep-in-arr [of g]* **by** *metis*
qed

Canonical arrows are invertible, and their inverses can be obtained syntactically.

lemma *inverse-arrows-can*:
assumes *can f*
shows *inverse-arrows f (mkarr (Inv (DOM f \lfloor) \cdot $\lfloor rep f \rfloor$ \cdot COD f \rfloor))*
proof
let $?t = (Inv (DOM f \lfloor) \cdot \lfloor rep f \rfloor \cdot COD f \rfloor)$
have $1: rep f \in f \wedge Arr (rep f) \wedge Can (rep f) \wedge Ide \lfloor rep f \rfloor$
using *assms can-def-alt rep-in-arr rep-in-arr(1) Can-rep-can* **by** *simp*
hence $2: \lfloor DOM f \rfloor = \lfloor COD f \rfloor$
using *Diagonalize-in-Hom [of rep f] Ide-in-Hom* **by** *auto*
have $3: Can ?t$
using *assms 1 2 Can-red Ide-implies-Can Diagonalize-in-Hom Inv-preserves-Can Arr-implies-Ide-Cod Arr-implies-Ide-Dom Diag-Diagonalize*
by *simp*
have $4: DOM f = Cod ?t$
using *assms can-def Can-red*
by (*simp add: Arr-implies-Ide-Dom Inv-preserves-Can(3)*)
have $5: COD f = Dom ?t$

```

    using assms can-def Can-red Arr-rep Arr-implies-Ide-Cod by simp
have 6: antipar f (mkarr ?t)
    using assms 3 4 5 dom-char cod-char can-def cod-mkarr dom-mkarr Can-implies-Arr
    by simp
show ide (f · mkarr ?t)
proof –
    have 7: par (f · mkarr ?t) (dom (f · mkarr ?t))
        using assms 6 by auto
    moreover have can (f · mkarr ?t)
    proof –
        have 8: Comp (rep f) ?t ∈ (f · mkarr ?t)
            using assms 1 3 4 6 can-implies-arr Arr-in-mkarr COD-mkarr Comp-in-comp-ARR
            Can-implies-Arr arr-iff-ARR seq-char'
        by meson
    moreover have Can (rep f · ?t)
        using 1 3 7 8 mkarr-memb(1) by (metis Arr.simps(4) Can.simps(4))
    ultimately show ?thesis
        using can-mkarr-Can 7 mkarr-memb(2) by metis
    qed
    moreover have can (dom (f · mkarr ?t))
        using 7 ide-implies-can by force
    ultimately have f · mkarr ?t = dom (f · mkarr ?t)
        using can-coherence by meson
    thus ?thesis
        using 7 ide-dom by metis
    qed
show ide (mkarr ?t · f)
proof –
    have 7: par (mkarr ?t · f) (cod (mkarr ?t · f))
        using assms 6 by auto
    moreover have can (mkarr ?t · f)
    proof –
        have 8: Comp ?t (rep f) ∈ mkarr ?t · f
            using assms 1 3 6 7 Arr-in-mkarr Comp-in-comp-ARR Can-implies-Arr arr-char
            comp-def
        by meson
    moreover have Can (?t · rep f)
        using 1 3 7 8 mkarr-memb(1) by (metis Arr.simps(4) Can.simps(4))
    ultimately show ?thesis
        using can-mkarr-Can 7 mkarr-memb(2) by metis
    qed
    moreover have can (cod (mkarr ?t · f))
        using 7 ide-implies-can by force
    ultimately have mkarr ?t · f = cod (mkarr ?t · f)
        using can-coherence by meson
    thus ?thesis
        using 7 can-implies-arr ide-cod by metis
    qed
qed

```



```

lemma inv-mkarr [simp]:
assumes Can t
shows inv (mkarr t) = mkarr (Inv t)
proof –
  have t: Can t ∧ Arr t ∧ Can (Inv t) ∧ Arr (Inv t) ∧ Ide (Dom t) ∧ Ide (Cod t)
    using assms Can-implies-Arr Arr-implies-Ide-Dom Arr-implies-Ide-Cod
      Inv-preserves-Can
    by simp
  have inverse-arrows (mkarr t) (mkarr (Inv t))
proof
  show ide (mkarr t · mkarr (Inv t))
proof –
    have mkarr (Cod t) = mkarr (Comp t (Inv t))
    using t Inv-in-Hom Ide-in-Hom Diagonalize-Inv Diag-Diagonalize Diagonalize-preserves-Can
      by (intro mkarr-eqI, auto)
    also have ... = mkarr t · mkarr (Inv t)
      using t comp-mkarr Inv-in-Hom by simp
    finally have mkarr (Cod t) = mkarr t · mkarr (Inv t)
      by blast
    thus ?thesis using t ide-mkarr-Ide [of Cod t] by simp
qed
  show ide (mkarr (Inv t) · mkarr t)
proof –
    have mkarr (Dom t) = mkarr (Inv t · t)
    using t Inv-in-Hom Ide-in-Hom Diagonalize-Inv Diag-Diagonalize Diagonalize-preserves-Can
      by (intro mkarr-eqI, auto)
    also have ... = mkarr (Inv t) · mkarr t
      using t comp-mkarr Inv-in-Hom by simp
    finally have mkarr (Dom t) = mkarr (Inv t) · mkarr t
      by blast
    thus ?thesis using t ide-mkarr-Ide [of Dom t] by simp
qed
qed
thus ?thesis using inverse-unique by auto
qed

```

```

lemma iso-can:
assumes can f
shows iso f
  using assms inverse-arrows-can by auto

```

The following function produces the unique canonical arrow between two given objects, if such an arrow exists.

```

definition mkcan
where mkcan a b = mkarr (Inv (COD b↓) · (DOM a↓))

```

```

lemma can-mkcan:
assumes ide a and ide b and  $[DOM a] = [COD b]$ 

```

shows $\text{can} (\text{mkcan } a \ b)$ **and** $\llbracket \text{mkcan } a \ b : a \rightarrow b \rrbracket$
proof –
show $\text{can} (\text{mkcan } a \ b)$
using *assms mkcan-def Arr-rep Arr-implies-Ide-Dom Arr-implies-Ide-Cod Can-red Inv-preserves-Can can-mkarr-Can*
by *simp*
show $\llbracket \text{mkcan } a \ b : a \rightarrow b \rrbracket$
using *assms mkcan-def Arr-rep Arr-implies-Ide-Dom Arr-implies-Ide-Cod Can-red Inv-in-Hom dom-char [of a] cod-char [of b] mkarr-rep mkarr-in-hom can-implies-arr*
by *auto*
qed

lemma *dom-mkcan*:
assumes *ide a and ide b and* $\llbracket \text{DOM } a \rrbracket = \llbracket \text{COD } b \rrbracket$
shows $\text{dom} (\text{mkcan } a \ b) = a$
using *assms can-mkcan by blast*

lemma *cod-mkcan*:
assumes *ide a and ide b and* $\llbracket \text{DOM } a \rrbracket = \llbracket \text{COD } b \rrbracket$
shows $\text{cod} (\text{mkcan } a \ b) = b$
using *assms can-mkcan by blast*

lemma *can-coherence'*:
assumes *can f*
shows $\text{mkcan} (\text{dom } f) (\text{cod } f) = f$
proof –
have $\text{Ide} \llbracket \text{rep } f \rrbracket$
using *assms Ide-Diagonalize-Can Can-rep-can by simp*
hence $\text{Dom} \llbracket \text{rep } f \rrbracket = \text{Cod} \llbracket \text{rep } f \rrbracket$
using *Ide-in-Hom by simp*
hence $\llbracket \text{DOM } f \rrbracket = \llbracket \text{COD } f \rrbracket$
using *assms can-implies-arr Arr-rep Diagonalize-in-Hom by simp*
moreover have $\text{DOM } f = \text{DOM} (\text{dom } f)$
using *assms can-implies-arr dom-char rep-mkarr Arr-implies-Ide-Dom Ide-implies-Arr Par-Arr-norm [of DOM f] Ide-in-Hom*
by *auto*
moreover have $\text{COD } f = \text{COD} (\text{cod } f)$
using *assms can-implies-arr cod-char rep-mkarr Arr-implies-Ide-Cod Ide-implies-Arr Par-Arr-norm [of COD f] Ide-in-Hom*
by *auto*
ultimately have $\text{can} (\text{mkcan} (\text{dom } f) (\text{cod } f)) \wedge \text{par } f (\text{mkcan} (\text{dom } f) (\text{cod } f))$
using *assms can-implies-arr can-mkcan dom-mkcan cod-mkcan by simp*
thus ?thesis using *assms can-coherence by blast*
qed

lemma *Ide-Diagonalize-rep-ide*:
assumes *ide a*
shows $\text{Ide} \llbracket \text{rep } a \rrbracket$
using *assms ide-implies-can can-def-alt rep-in-arr by simp*

```

lemma Diagonalize-DOM:
assumes arr f
shows  $\llbracket DOM f \rrbracket = Dom \llbracket rep f \rrbracket$ 
  using assms Diag-Diagonalize by simp

lemma Diagonalize-COD:
assumes arr f
shows  $\llbracket COD f \rrbracket = Cod \llbracket rep f \rrbracket$ 
  using assms Diag-Diagonalize by simp

lemma Diagonalize-rep-preserves-seq:
assumes seq g f
shows  $Seq \llbracket rep g \rrbracket \llbracket rep f \rrbracket$ 
  using assms Diagonalize-DOM Diagonalize-COD Diag-implies-Arr Diag-Diagonalize(1)
  rep-preserves-seq
  by force

lemma Dom-Diagonalize-rep:
assumes arr f
shows  $Dom \llbracket rep f \rrbracket = \llbracket rep (dom f) \rrbracket$ 
  using assms Diagonalize-rep-preserves-seq [of f dom f] Ide-Diagonalize-rep-ide Ide-in-Hom
  by simp

lemma Cod-Diagonalize-rep:
assumes arr f
shows  $Cod \llbracket rep f \rrbracket = \llbracket rep (cod f) \rrbracket$ 
  using assms Diagonalize-rep-preserves-seq [of cod f f] Ide-Diagonalize-rep-ide Ide-in-Hom
  by simp

lemma mkarr-Diagonalize-rep:
assumes arr f and Diag (DOM f) and Diag (COD f)
shows  $mkarr \llbracket rep f \rrbracket = f$ 
proof –
  have  $mkarr (rep f) = mkarr \llbracket rep f \rrbracket$ 
    using assms rep-in-Hom Diagonalize-in-Hom Diag-Diagonalize Diagonalize-Diag
    by (intro mkarr-eqI, simp-all)
  thus ?thesis using assms mkarr-rep by auto
qed

```

We define tensor product of arrows via the constructor (\otimes) on terms.

```

definition tensorFMC (infixr  $\langle \otimes \rangle$  53)
  where  $f \otimes g \equiv (if\ arr\ f \wedge arr\ g\ then\ mkarr\ (rep\ f \otimes rep\ g)\ else\ null)$ 

```

```

lemma arr-tensor [simp]:
assumes arr f and arr g
shows  $arr (f \otimes g)$ 
  using assms tensorFMC-def arr-mkarr by simp

```

lemma *rep-tensor*:
assumes *arr f* **and** *arr g*
shows $\text{rep } (f \otimes g) = \|\text{rep } f \otimes \text{rep } g\|$
using *assms tensor_{FM C}-def rep-mkarr* **by** *simp*

lemma *Par-memb-rep*:
assumes *arr f* **and** $t \in f$
shows $\text{Par } t (\text{rep } f)$
using *assms mkarr-memb* **apply** *simp*
using *rep-in-Hom Dom-memb Cod-memb* **by** *metis*

lemma *Tensor-in-tensor* [*intro*]:
assumes *arr f* **and** *arr g* **and** $t \in f$ **and** $u \in g$
shows $t \otimes u \in f \otimes g$
proof –
 have $\text{equiv } (t \otimes u) (\text{rep } f \otimes \text{rep } g)$
 proof –
 have $1: \text{Par } (t \otimes u) (\text{rep } f \otimes \text{rep } g)$
 proof –
 have $\text{Par } t (\text{rep } f) \wedge \text{Par } u (\text{rep } g)$ **using** *assms Par-memb-rep* **by** *blast*
 thus *?thesis* **by** *simp*
 qed
 moreover **have** $\lfloor t \otimes u \rfloor = \lfloor \text{rep } f \otimes \text{rep } g \rfloor$
 using *assms 1 equiv-iff-eq-norm rep-mkarr norm-norm mkarr-memb(2)*
 by (*metis Arr.simps(3) Diagonalize.simps(3)*)
 ultimately show *?thesis* **by** *simp*
qed
thus *?thesis*
using *assms tensor_{FM C}-def mkarr-def* **by** *simp*
qed

lemma *DOM-tensor* [*simp*]:
assumes *arr f* **and** *arr g*
shows $\text{DOM } (f \otimes g) = \text{DOM } f \otimes \text{DOM } g$
by (*metis (no-types, lifting) DOM-mkarr Dom.simps(3) mkarr-extensionality arr-char arr-tensor assms(1) assms(2) tensor_{FM C}-def*)

lemma *COD-tensor* [*simp*]:
assumes *arr f* **and** *arr g*
shows $\text{COD } (f \otimes g) = \text{COD } f \otimes \text{COD } g$
by (*metis (no-types, lifting) COD-mkarr Cod.simps(3) mkarr-extensionality arr-char arr-tensor assms(1) assms(2) tensor_{FM C}-def*)

lemma *tensor-in-hom* [*simp*]:
assumes $\langle f : a \rightarrow b \rangle$ **and** $\langle g : c \rightarrow d \rangle$
shows $\langle f \otimes g : a \otimes c \rightarrow b \otimes d \rangle$
proof –
 have $f: \text{arr } f \wedge \text{dom } f = a \wedge \text{cod } f = b$ **using** *assms(1)* **by** *auto*
 have $g: \text{arr } g \wedge \text{dom } g = c \wedge \text{cod } g = d$ **using** *assms(2)* **by** *auto*

```

have  $\text{dom } (f \otimes g) = \text{dom } f \otimes \text{dom } g$ 
  using  $f\ g\ \text{arr-tensor dom-char Tensor-in-tensor [of dom } f\ \text{dom } g\ \text{DOM } f\ \text{DOM } g]$ 
     $\text{DOM-in-dom mkarr-memb}(?)\ \text{DOM-tensor arr-dom-iff-arr}$ 
  by metis
moreover have  $\text{cod } (f \otimes g) = \text{cod } f \otimes \text{cod } g$ 
  using  $f\ g\ \text{arr-tensor cod-char Tensor-in-tensor [of cod } f\ \text{cod } g\ \text{COD } f\ \text{COD } g]$ 
     $\text{COD-in-cod mkarr-memb}(?)\ \text{COD-tensor arr-cod-iff-arr}$ 
  by metis
ultimately show ?thesis using assms arr-tensor by blast
qed

lemma dom-tensor [simp]:
assumes  $\text{arr } f$  and  $\text{arr } g$ 
shows  $\text{dom } (f \otimes g) = \text{dom } f \otimes \text{dom } g$ 
  using assms tensor-in-hom [of f] by blast

lemma cod-tensor [simp]:
assumes  $\text{arr } f$  and  $\text{arr } g$ 
shows  $\text{cod } (f \otimes g) = \text{cod } f \otimes \text{cod } g$ 
  using assms tensor-in-hom [of f] by blast

lemma tensor-mkarr [simp]:
assumes  $\text{Arr } t$  and  $\text{Arr } u$ 
shows  $\text{mkarr } t \otimes \text{mkarr } u = \text{mkarr } (t \otimes u)$ 
  using assms by (meson Tensor-in-tensor arr-char Arr-in-mkarr arr-mkarr arr-tensor)

lemma tensor-preserves-ide:
assumes ide a and ide b
shows ide (a  $\otimes$  b)
proof –
  have can (a  $\otimes$  b)
    using assms tensorFM C-def Can-rep-can ide-implies-can can-mkarr-Can by simp
  moreover have  $\text{dom } (a \otimes b) = \text{cod } (a \otimes b)$ 
    using assms tensor-in-hom by simp
  ultimately show ?thesis using ide-char by metis
qed

lemma tensor-preserves-can:
assumes can f and can g
shows can (f  $\otimes$  g)
  using assms can-implies-arr Can-rep-can tensorFM C-def can-mkarr-Can by simp

lemma comp-preserves-can:
assumes can f and can g and  $\text{dom } f = \text{cod } g$ 
shows can (f  $\cdot$  g)
proof –
  have  $1: \text{ARR } f \wedge \text{ARR } g \wedge \text{DOM } f = \text{COD } g$ 
    using assms can-implies-arr arr-iff-ARR Arr-implies-Ide-Cod Arr-implies-Ide-Dom
    mkarr-inj-on-Ide cod-char dom-char

```

by *simp*
hence $Can (rep f \cdot rep g)$
using *assms can-implies-arr Can-rep-can* **by** *force*
thus *?thesis*
using *assms 1 can-implies-arr comp-char can-mkarr-Can seq-char'* **by** *simp*
qed

The remaining structure required of a monoidal category is also defined syntactically.

definition $unity_{FMC} :: 'c\ arr$ ($\langle \mathcal{I} \rangle$)
where $\mathcal{I} = mkarr\ \mathcal{I}$

definition $lunit_{FMC} :: 'c\ arr \Rightarrow 'c\ arr$ ($\langle l[-] \rangle$)
where $l[a] = mkarr\ l[rep\ a]$

definition $runit_{FMC} :: 'c\ arr \Rightarrow 'c\ arr$ ($\langle r[-] \rangle$)
where $r[a] = mkarr\ r[rep\ a]$

definition $assoc_{FMC} :: 'c\ arr \Rightarrow 'c\ arr \Rightarrow 'c\ arr \Rightarrow 'c\ arr$ ($\langle a[-, -, -] \rangle$)
where $a[a, b, c] = mkarr\ a[rep\ a, rep\ b, rep\ c]$

lemma *can-lunit*:
assumes *ide a*
shows *can l[a]*
using *assms lunit_{FMC}-def can-mkarr-Can*
by (*simp add: Can-rep-can ide-implies-can*)

lemma *lunit-in-hom*:
assumes *ide a*
shows $\langle l[a] : \mathcal{I} \otimes a \rightarrow a \rangle$
proof –
have $dom\ l[a] = \mathcal{I} \otimes a$
using *assms lunit_{FMC}-def unity_{FMC}-def Ide-implies-Arr dom-mkarr dom-char ten-*
sor-mkarr
Arr-rep
by (*metis Arr.simps(2) Arr.simps(5) Arr-implies-Ide-Dom Dom.simps(5)*
ideD(1) ideD(2))
moreover **have** $cod\ l[a] = a$
using *assms lunit_{FMC}-def rep-in-arr(1) cod-mkarr cod-char ideD(3)* **by** *auto*
ultimately show *?thesis*
using *assms arr-cod-iff-arr* **by** (*intro in-homI, fastforce*)
qed

lemma *arr-lunit [simp]*:
assumes *ide a*
shows *arr l[a]*
using *assms can-lunit can-implies-arr* **by** *simp*

lemma *dom-lunit [simp]*:
assumes *ide a*

shows $\text{dom } l[a] = \mathcal{I} \otimes a$
using *assms lunit-in-hom by auto*

lemma *cod-lunit [simp]*:
assumes *ide a*
shows $\text{cod } l[a] = a$
using *assms lunit-in-hom by auto*

lemma *can-runit*:
assumes *ide a*
shows *can r[a]*
using *assms runit_{FM C}-def can-mkarr-Can*
by (*simp add: Can-rep-can ide-implies-can*)

lemma *runit-in-hom [simp]*:
assumes *ide a*
shows $\langle r[a] : a \otimes \mathcal{I} \rightarrow a \rangle$
proof –
have $\text{dom } r[a] = a \otimes \mathcal{I}$
using *assms Arr-rep Arr.simps(2) Arr.simps(7) Arr-implies-Ide-Dom Dom.simps(7)*
Ide-implies-Arr dom-mkarr dom-char ideD(1) ideD(2) runit_{FM C}-def tensor-mkarr
unity_{FM C}-def
by *metis*
moreover have $\text{cod } r[a] = a$
using *assms runit_{FM C}-def rep-in-arr(1) cod-mkarr cod-char ideD(3) by auto*
ultimately show *?thesis*
using *assms arr-cod-iff-arr by (intro in-homI, fastforce)*
qed

lemma *arr-runit [simp]*:
assumes *ide a*
shows *arr r[a]*
using *assms can-runit can-implies-arr by simp*

lemma *dom-runit [simp]*:
assumes *ide a*
shows $\text{dom } r[a] = a \otimes \mathcal{I}$
using *assms runit-in-hom by blast*

lemma *cod-runit [simp]*:
assumes *ide a*
shows $\text{cod } r[a] = a$
using *assms runit-in-hom by blast*

lemma *can-assoc*:
assumes *ide a and ide b and ide c*
shows *can a[a, b, c]*
using *assms assoc_{FM C}-def can-mkarr-Can*
by (*simp add: Can-rep-can ide-implies-can*)

lemma *assoc-in-hom*:
assumes *ide a and ide b and ide c*
shows $\llbracket a[a, b, c] : (a \otimes b) \otimes c \rightarrow a \otimes b \otimes c \rrbracket$
proof –
 have $\text{dom } a[a, b, c] = (a \otimes b) \otimes c$
 proof –
 have $\text{dom } a[a, b, c] = \text{mkarr } (\text{Dom } \mathbf{a}[\text{rep } a, \text{rep } b, \text{rep } c])$
 using *assms assoc_{FM C}-def rep-in-arr(1) by simp*
 also have $\dots = \text{mkarr } ((\text{DOM } a \otimes \text{DOM } b) \otimes \text{DOM } c)$
 by *simp*
 also have $\dots = (a \otimes b) \otimes c$
 by (*metis mkarr-extensionality arr-tensor assms dom-char*
 ideD(1) ideD(2) not-arr-null null-char tensor-mkarr)
 finally show *?thesis by blast*
qed
moreover have $\text{cod } a[a, b, c] = a \otimes b \otimes c$
proof –
 have $\text{cod } a[a, b, c] = \text{mkarr } (\text{Cod } \mathbf{a}[\text{rep } a, \text{rep } b, \text{rep } c])$
 using *assms assoc_{FM C}-def rep-in-arr(1) by simp*
 also have $\dots = \text{mkarr } (\text{COD } a \otimes \text{COD } b \otimes \text{COD } c)$
 by *simp*
 also have $\dots = a \otimes b \otimes c$
 by (*metis mkarr-extensionality arr-tensor assms(1) assms(2) assms(3) cod-char*
 ideD(1) ideD(3) not-arr-null null-char tensor-mkarr)
 finally show *?thesis by blast*
qed
moreover have $\text{arr } a[a, b, c]$
 using *assms assoc_{FM C}-def rep-in-arr(1) arr-mkarr by simp*
ultimately show *?thesis by auto*
qed

lemma *arr-assoc [simp]*:
assumes *ide a and ide b and ide c*
shows $\text{arr } a[a, b, c]$
 using *assms can-assoc can-implies-arr by simp*

lemma *dom-assoc [simp]*:
assumes *ide a and ide b and ide c*
shows $\text{dom } a[a, b, c] = (a \otimes b) \otimes c$
 using *assms assoc-in-hom by blast*

lemma *cod-assoc [simp]*:
assumes *ide a and ide b and ide c*
shows $\text{cod } a[a, b, c] = a \otimes b \otimes c$
 using *assms assoc-in-hom by blast*

lemma *ide-unity [simp]*:
shows *ide I*

using *unity_{FMC-def} Arr.simps(2) Dom.simps(2) arr-mkarr dom-mkarr ide-dom*
by *metis*

lemma *Unity-in-unity [simp]:*
shows $\mathcal{I} \in \mathcal{I}$
using *unity_{FMC-def} Arr-in-mkarr* **by** *simp*

lemma *rep-unity [simp]:*
shows $\text{rep } \mathcal{I} = \|\mathcal{I}\|$
using *unity_{FMC-def} rep-mkarr* **by** *simp*

lemma *Lunit-in-lunit [intro]:*
assumes *arr f* **and** $t \in f$
shows $\mathbb{l}[t] \in \mathbb{l}[f]$
proof –
have $\text{Arr } t \wedge \text{Arr } (\text{rep } f) \wedge \text{Dom } t = \text{DOM } f \wedge \text{Cod } t = \text{COD } f \wedge [t] = [\text{rep } f]$
using *assms*
by (*metis mkarr-memb(1) mkarr-memb(2) rep-mkarr rep-in-arr(1) equiv-iff-eq-norm norm-rep*)
thus *?thesis*
by (*simp add: mkarr-def lunit_{FMC-def}*)
qed

lemma *Runit-in-runit [intro]:*
assumes *arr f* **and** $t \in f$
shows $\mathbb{r}[t] \in \mathbb{r}[f]$
proof –
have $\text{Arr } t \wedge \text{Arr } (\text{rep } f) \wedge \text{Dom } t = \text{DOM } f \wedge \text{Cod } t = \text{COD } f \wedge [t] = [\text{rep } f]$
using *assms*
by (*metis mkarr-memb(1) mkarr-memb(2) rep-mkarr rep-in-arr(1) equiv-iff-eq-norm norm-rep*)
thus *?thesis*
by (*simp add: mkarr-def runit_{FMC-def}*)
qed

lemma *Assoc-in-assoc [intro]:*
assumes *arr f* **and** *arr g* **and** *arr h*
and $t \in f$ **and** $u \in g$ **and** $v \in h$
shows $\mathbb{a}[t, u, v] \in \mathbb{a}[f, g, h]$
proof –
have $\text{Arr } t \wedge \text{Arr } (\text{rep } f) \wedge \text{Dom } t = \text{DOM } f \wedge \text{Cod } t = \text{COD } f \wedge [t] = [\text{rep } f]$
using *assms*
by (*metis mkarr-memb(1) rep-mkarr rep-in-arr(1) equiv-iff-eq-norm mkarr-memb(2) norm-rep*)
moreover **have** $\text{Arr } u \wedge \text{Arr } (\text{rep } g) \wedge \text{Dom } u = \text{DOM } g \wedge \text{Cod } u = \text{COD } g \wedge [u] = [\text{rep } g]$
using *assms*
by (*metis mkarr-memb(1) rep-mkarr rep-in-arr(1) equiv-iff-eq-norm mkarr-memb(2) norm-rep*)

moreover have $Arr\ v \wedge Arr\ (rep\ h) \wedge Dom\ v = DOM\ h \wedge Cod\ v = COD\ h \wedge$
 $\quad [v] = [rep\ h]$
using *assms*
by (*metis mkarr-memb(1) rep-mkarr rep-in-arr(1) equiv-iff-eq-norm mkarr-memb(2)*
norm-rep)
ultimately show *?thesis*
using *assoc_FMC-def mkarr-def* **by** *simp*
qed

At last, we can show that we've constructed a monoidal category.

interpretation *EMC: elementary-monoidal-category*
 $comp\ tensor_{FMC}\ unity_{FMC}\ lunit_{FMC}\ runit_{FMC}\ assoc_{FMC}$

proof

show *ide I* **using** *ide-unity* **by** *auto*
show $\bigwedge a. ide\ a \implies \llbracket l[a] : \mathcal{I} \otimes a \rightarrow a \rrbracket$ **by** *auto*
show $\bigwedge a. ide\ a \implies \llbracket r[a] : a \otimes \mathcal{I} \rightarrow a \rrbracket$ **by** *auto*
show $\bigwedge a. ide\ a \implies iso\ l[a]$ **using** *can-lunit iso-can* **by** *auto*
show $\bigwedge a. ide\ a \implies iso\ r[a]$ **using** *can-runit iso-can* **by** *auto*
show $\bigwedge a\ b\ c. \llbracket ide\ a; ide\ b; ide\ c \rrbracket \implies \llbracket a[a, b, c] : (a \otimes b) \otimes c \rightarrow a \otimes b \otimes c \rrbracket$ **by** *auto*
show $\bigwedge a\ b\ c. \llbracket ide\ a; ide\ b; ide\ c \rrbracket \implies iso\ a[a, b, c]$ **using** *can-assoc iso-can* **by** *auto*
show $\bigwedge a\ b. \llbracket ide\ a; ide\ b \rrbracket \implies ide\ (a \otimes b)$ **using** *tensor-preserves-ide* **by** *auto*
fix *f a b g c d*
show $\llbracket \llbracket f : a \rightarrow b \rrbracket; \llbracket g : c \rightarrow d \rrbracket \rrbracket \implies \llbracket f \otimes g : a \otimes c \rightarrow b \otimes d \rrbracket$
using *tensor-in-hom* **by** *auto*
next

Naturality of left unitor.

fix *f*
assume *f: arr f*
show $l[cod\ f] \cdot (\mathcal{I} \otimes f) = f \cdot l[dom\ f]$
proof (*intro arr-eqI*)
show *par* ($l[cod\ f] \cdot (\mathcal{I} \otimes f)$) ($f \cdot l[dom\ f]$)
using *f* **by** *simp*
show $l[COD\ f] \cdot (\mathcal{I} \otimes rep\ f) \in l[cod\ f] \cdot (\mathcal{I} \otimes f)$
using *f* **by** *fastforce*
show $rep\ f \cdot l[DOM\ f] \in f \cdot l[dom\ f]$
using *f* **by** *fastforce*
show $l[COD\ f] \cdot (\mathcal{I} \otimes rep\ f) = [rep\ f \cdot l[DOM\ f]]$
using *f* **by** (*simp add: Diag-Diagonalize(1) Diagonalize-DOM Diagonalize-COD*)
qed

Naturality of right unitor.

show $r[cod\ f] \cdot (f \otimes \mathcal{I}) = f \cdot r[dom\ f]$
proof (*intro arr-eqI*)
show *par* ($r[cod\ f] \cdot (f \otimes \mathcal{I})$) ($f \cdot r[dom\ f]$)
using *f* **by** *simp*
show $r[COD\ f] \cdot (rep\ f \otimes \mathcal{I}) \in r[cod\ f] \cdot (f \otimes \mathcal{I})$
using *f* **by** *fastforce*
show $rep\ f \cdot r[DOM\ f] \in f \cdot r[dom\ f]$

```

    using f by fastforce
  show [r[COD f] · (rep f ⊗ I)] = [rep f · r[DOM f]]
    using f by (simp add: Diag-Diagonalize(1) Diagonalize-DOM Diagonalize-COD)
qed
next

```

Naturality of associator.

```

fix f0 :: 'c arr and f1 f2
assume f0: arr f0 and f1: arr f1 and f2: arr f2
show a[cod f0, cod f1, cod f2] · ((f0 ⊗ f1) ⊗ f2)
  = (f0 ⊗ f1 ⊗ f2) · a[dom f0, dom f1, dom f2]
proof (intro arr-eqI)
  show 1: par (a[cod f0, cod f1, cod f2] · ((f0 ⊗ f1) ⊗ f2))
    ((f0 ⊗ f1 ⊗ f2) · a[dom f0, dom f1, dom f2])
    using f0 f1 f2 by force
  show a[rep (cod f0), rep (cod f1), rep (cod f2)] · ((rep f0 ⊗ rep f1) ⊗ rep f2)
    ∈ a[cod f0, cod f1, cod f2] · ((f0 ⊗ f1) ⊗ f2)
    using f0 f1 f2 by fastforce
  show (rep f0 ⊗ rep f1 ⊗ rep f2) · a[rep (dom f0), rep (dom f1), rep (dom f2)]
    ∈ (f0 ⊗ f1 ⊗ f2) · a[dom f0, dom f1, dom f2]
    using f0 f1 f2 by fastforce
  show [a[rep (cod f0), rep (cod f1), rep (cod f2)] · ((rep f0 ⊗ rep f1) ⊗ rep f2)]
    = [(rep f0 ⊗ rep f1 ⊗ rep f2) · a[rep (dom f0), rep (dom f1), rep (dom f2)]]
  proof -
    have [a[rep (cod f0), rep (cod f1), rep (cod f2)] · ((rep f0 ⊗ rep f1) ⊗ rep f2)]
      = [rep f0] [⊗] [rep f1] [⊗] [rep f2]
    proof -
      have b0: [rep (cod f0)] = Cod [rep f0]
        using f0 Cod-Diagonalize-rep by simp
      have b1: [rep (cod f1)] = Cod [rep f1]
        using f1 Cod-Diagonalize-rep by simp
      have b2: [rep (cod f2)] = Cod [rep f2]
        using f2 Cod-Diagonalize-rep by simp
      have [a[rep (cod f0), rep (cod f1), rep (cod f2)] · ((rep f0 ⊗ rep f1) ⊗ rep f2)]
        = ([rep (cod f0)] [⊗] [rep (cod f1)] [⊗] [rep (cod f2)]) [·]
          ([rep f0] [⊗] [rep f1] [⊗] [rep f2])
        using f0 f1 f2 using Diag-Diagonalize(1) TensorDiag-assoc by auto
      also have ... = [rep (cod f0)] [·] [rep f0] [⊗]
        [rep (cod f1)] [·] [rep f1] [⊗] [rep (cod f2)] [·] [rep f2]
    proof -
      have Seq [rep (cod f0)] [rep f0] ∧ Seq [rep (cod f1)] [rep f1] ∧
        Seq [rep (cod f2)] [rep f2]
    using f0 f1 f2 rep-in-Hom Diagonalize-in-Hom Dom-Diagonalize-rep Cod-Diagonalize-rep
    by auto
    thus ?thesis
    using f0 f1 f2 b0 b1 b2 TensorDiag-in-Hom TensorDiag-preserves-Diag
      Diag-Diagonalize Arr-implies-Ide-Dom Arr-implies-Ide-Cod
      CompDiag-TensorDiag
    by simp

```

qed
also have ... = $\llbracket \text{rep } f0 \rrbracket \llbracket \otimes \rrbracket \llbracket \text{rep } f1 \rrbracket \llbracket \otimes \rrbracket \llbracket \text{rep } f2 \rrbracket$
proof –
have $\llbracket \text{rep } (\text{cod } f0) \rrbracket \llbracket \cdot \rrbracket \llbracket \text{rep } f0 \rrbracket = \llbracket \text{rep } f0 \rrbracket$
using $f0\ b0\ \text{CompDiag-Cod-Diag}$ [of $\llbracket \text{rep } f0 \rrbracket$] *Diag-Diagonalize*
by simp
moreover have $\llbracket \text{rep } (\text{cod } f1) \rrbracket \llbracket \cdot \rrbracket \llbracket \text{rep } f1 \rrbracket = \llbracket \text{rep } f1 \rrbracket$
using $f1\ b1\ \text{CompDiag-Cod-Diag}$ [of $\llbracket \text{rep } f1 \rrbracket$] *Diag-Diagonalize*
by simp
moreover have $\llbracket \text{rep } (\text{cod } f2) \rrbracket \llbracket \cdot \rrbracket \llbracket \text{rep } f2 \rrbracket = \llbracket \text{rep } f2 \rrbracket$
using $f2\ b2\ \text{CompDiag-Cod-Diag}$ [of $\llbracket \text{rep } f2 \rrbracket$] *Diag-Diagonalize*
by simp
ultimately show *?thesis* **by argo**
qed
finally show *?thesis* **by blast**
qed
also have ... = $\llbracket (\text{rep } f0 \otimes \text{rep } f1 \otimes \text{rep } f2) \cdot \mathbf{a}[\text{rep } (\text{dom } f0), \text{rep } (\text{dom } f1), \text{rep } (\text{dom } f2)] \rrbracket$
proof –
have $a0: \llbracket \text{rep } (\text{dom } f0) \rrbracket = \text{Dom } \llbracket \text{rep } f0 \rrbracket$
using $f0\ \text{Dom-Diagonalize-rep}$ **by simp**
have $a1: \llbracket \text{rep } (\text{dom } f1) \rrbracket = \text{Dom } \llbracket \text{rep } f1 \rrbracket$
using $f1\ \text{Dom-Diagonalize-rep}$ **by simp**
have $a2: \llbracket \text{rep } (\text{dom } f2) \rrbracket = \text{Dom } \llbracket \text{rep } f2 \rrbracket$
using $f2\ \text{Dom-Diagonalize-rep}$ **by simp**
have $\llbracket (\text{rep } f0 \otimes \text{rep } f1 \otimes \text{rep } f2) \cdot \mathbf{a}[\text{rep } (\text{dom } f0), \text{rep } (\text{dom } f1), \text{rep } (\text{dom } f2)] \rrbracket$
= $(\llbracket \text{rep } f0 \rrbracket \llbracket \otimes \rrbracket \llbracket \text{rep } f1 \rrbracket \llbracket \otimes \rrbracket \llbracket \text{rep } f2 \rrbracket) \llbracket \cdot \rrbracket$
 $(\llbracket \text{rep } (\text{dom } f0) \rrbracket \llbracket \otimes \rrbracket \llbracket \text{rep } (\text{dom } f1) \rrbracket \llbracket \otimes \rrbracket \llbracket \text{rep } (\text{dom } f2) \rrbracket)$
using $f0\ f1\ f2\ \text{using}$ *Diag-Diagonalize(1)* *TensorDiag-assoc* **by auto**
also have ... = $\llbracket \text{rep } f0 \rrbracket \llbracket \cdot \rrbracket \llbracket \text{rep } (\text{dom } f0) \rrbracket \llbracket \otimes \rrbracket \llbracket \text{rep } f1 \rrbracket \llbracket \cdot \rrbracket \llbracket \text{rep } (\text{dom } f1) \rrbracket \llbracket \otimes \rrbracket$
 $\llbracket \text{rep } f2 \rrbracket \llbracket \cdot \rrbracket \llbracket \text{rep } (\text{dom } f2) \rrbracket$
proof –
have $\text{Seq } \llbracket \text{rep } f0 \rrbracket \llbracket \text{rep } (\text{dom } f0) \rrbracket \wedge \text{Seq } \llbracket \text{rep } f1 \rrbracket \llbracket \text{rep } (\text{dom } f1) \rrbracket \wedge$
 $\text{Seq } \llbracket \text{rep } f2 \rrbracket \llbracket \text{rep } (\text{dom } f2) \rrbracket$
using $f0\ f1\ f2\ \text{rep-in-Hom}$ *Diagonalize-in-Hom* *Dom-Diagonalize-rep* *Cod-Diagonalize-rep*
by auto
thus *?thesis*
using $f0\ f1\ f2\ a0\ a1\ a2\ \text{TensorDiag-in-Hom}$ *TensorDiag-preserves-Diag*
Diag-Diagonalize *Arr-implies-Ide-Dom* *Arr-implies-Ide-Cod*
CompDiag-TensorDiag
by force
qed
also have ... = $\llbracket \text{rep } f0 \rrbracket \llbracket \otimes \rrbracket \llbracket \text{rep } f1 \rrbracket \llbracket \otimes \rrbracket \llbracket \text{rep } f2 \rrbracket$
proof –
have $\llbracket \text{rep } f0 \rrbracket \llbracket \cdot \rrbracket \llbracket \text{rep } (\text{dom } f0) \rrbracket = \llbracket \text{rep } f0 \rrbracket$
using $f0\ a0\ \text{CompDiag-Diag-Dom}$ [of *Diagonalize (rep f0)*] *Diag-Diagonalize*
by simp
moreover have $\llbracket \text{rep } f1 \rrbracket \llbracket \cdot \rrbracket \llbracket \text{rep } (\text{dom } f1) \rrbracket = \llbracket \text{rep } f1 \rrbracket$
using $f1\ a1\ \text{CompDiag-Diag-Dom}$ [of *Diagonalize (rep f1)*] *Diag-Diagonalize*

```

    by simp
    moreover have [rep f2] [·] [rep (dom f2)] = [rep f2]
      using f2 a2 CompDiag-Diag-Dom [of Diagonalize (rep f2)] Diag-Diagonalize
      by simp
    ultimately show ?thesis by argo
  qed
  finally show ?thesis by argo
  qed
  finally show ?thesis by blast
  qed
  qed
  next

```

Tensor preserves composition (interchange).

```

fix f g f' g'
show [ seq g f; seq g' f' ] ==> (g ⊗ g') · (f ⊗ f') = g · f ⊗ g' · f'
proof -
  assume gf: seq g f
  assume gf': seq g' f'
  show ?thesis
  proof (intro arr-eqI)
    show par ((g ⊗ g') · (f ⊗ f')) (g · f ⊗ g' · f')
      using gf gf' by fastforce
    show (rep g ⊗ rep g') · (rep f ⊗ rep f') ∈ (g ⊗ g') · (f ⊗ f')
      using gf gf' by force
    show rep g · rep f ⊗ rep g' · rep f' ∈ g · f ⊗ g' · f'
      using gf gf'
      by (meson Comp-in-comp-ARR Tensor-in-tensor rep-in-arr seqE seq-char')
    show [(rep g ⊗ rep g') · (rep f ⊗ rep f')] = [rep g · rep f ⊗ rep g' · rep f']
    proof -
      have [(rep g ⊗ rep g') · (rep f ⊗ rep f')]
        = ([rep g] [⊗] [rep g']) [·] ([rep f] [⊗] [rep f'])
      by auto
      also have ... = [rep g] [·] [rep f] [⊗] [rep g'] [·] [rep f']
      using gf gf' Arr-rep Diagonalize-rep-preserves-seq
        CompDiag-TensorDiag [of [rep g] [rep g'] [rep f] [rep f']]
        Diag-Diagonalize Diagonalize-DOM Diagonalize-COD
      by force
      also have ... = [rep g · rep f ⊗ rep g' · rep f']
      by auto
    finally show ?thesis by blast
  qed
  qed
  qed
  next

```

The triangle.

```

fix a b
assume a: ide a

```

```

assume  $b$ : ide  $b$ 
show  $(a \otimes l[b]) \cdot a[a, \mathcal{I}, b] = r[a] \otimes b$ 
proof –
  have par  $((a \otimes l[b]) \cdot a[a, \mathcal{I}, b]) (r[a] \otimes b)$ 
    using  $a$   $b$  by simp
  moreover have can  $((a \otimes l[b]) \cdot a[a, \mathcal{I}, b])$ 
    using  $a$   $b$  ide-implies-can comp-preserves-can tensor-preserves-can can-assoc can-lunit
    by simp
  moreover have can  $(r[a] \otimes b)$ 
    using  $a$   $b$  ide-implies-can can-runit tensor-preserves-can by simp
  ultimately show ?thesis using can-coherence by blast
qed
next

```

The pentagon.

```

fix  $a$   $b$   $c$   $d$ 
assume  $a$ : ide  $a$ 
assume  $b$ : ide  $b$ 
assume  $c$ : ide  $c$ 
assume  $d$ : ide  $d$ 
show  $(a \otimes a[b, c, d]) \cdot a[a, b \otimes c, d] \cdot (a[a, b, c] \otimes d)$ 
   $= a[a, b, c \otimes d] \cdot a[a \otimes b, c, d]$ 
proof –
  let ?LHS  $= (a \otimes a[b, c, d]) \cdot a[a, b \otimes c, d] \cdot (a[a, b, c] \otimes d)$ 
  let ?RHS  $= a[a, b, c \otimes d] \cdot a[a \otimes b, c, d]$ 
  have par ?LHS ?RHS
    using  $a$   $b$   $c$   $d$  can-assoc tensor-preserves-ide by auto
  moreover have can ?LHS
    using  $a$   $b$   $c$   $d$  ide-implies-can comp-preserves-can tensor-preserves-can can-assoc
    tensor-preserves-ide
    by simp
  moreover have can ?RHS
    using  $a$   $b$   $c$   $d$  comp-preserves-can tensor-preserves-can can-assoc tensor-in-hom
    tensor-preserves-ide
    by simp
  ultimately show ?thesis using can-coherence by blast
qed
qed

```

lemma *is-elementary-monoidal-category*:

shows *elementary-monoidal-category*

comp T_{FMC} *unity* T_{FMC} *lunit* T_{FMC} *runit* T_{FMC} *assoc* T_{FMC}

..

abbreviation T_{FMC} **where** $T_{FMC} \equiv EMC.T$

abbreviation α_{FMC} **where** $\alpha_{FMC} \equiv EMC.\alpha$

abbreviation ι_{FMC} **where** $\iota_{FMC} \equiv EMC.\iota$

interpretation MC : *monoidal-category* *comp* T_{FMC} α_{FMC} ι_{FMC}

```

using EMC.induces-monoidal-category by auto

lemma induces-monoidal-category:
shows monoidal-category comp TFMC αFMC ℓFMC
  ..

end

sublocale free-monoidal-category ⊆
  elementary-monoidal-category
  comp tensorFMC unityFMC lunitFMC runitFMC assocFMC
using is-elementary-monoidal-category by auto

sublocale free-monoidal-category ⊆ monoidal-category comp TFMC αFMC ℓFMC
using induces-monoidal-category by auto

```

4.2 Proof of Freeness

Now we proceed on to establish the freeness of \mathcal{FC} : each functor from C to a monoidal category D extends uniquely to a strict monoidal functor from \mathcal{FC} to D .

```

context free-monoidal-category
begin

lemma rep-lunit:
assumes ide a
shows rep l[a] = ||l[rep a]||
  using assms Lunit-in-lunit [of a rep a] rep-in-arr norm-memb-eq-rep [of l[a]]
  by simp

lemma rep-runit:
assumes ide a
shows rep r[a] = ||r[rep a]||
  using assms Runit-in-runit [of a rep a] rep-in-arr norm-memb-eq-rep [of r[a]]
  by simp

lemma rep-assoc:
assumes ide a and ide b and ide c
shows rep a[a, b, c] = ||a[rep a, rep b, rep c]||
  using assms Assoc-in-assoc [of a b c rep a rep b rep c] rep-in-arr
  norm-memb-eq-rep [of a[a, b, c]]
  by simp

lemma mkarr-Unity:
shows mkarr I = I
  using unityFMC-def by simp

```

The unitors and associator were given syntactic definitions in terms of corresponding terms, but these were only for the special case of identity arguments (*i.e.* the components

of the natural transformations). We need to show that $mkarr$ gives the correct result for *all* terms.

lemma *mkarr-Lunit*:

assumes $Arr\ t$

shows $mkarr\ \mathbb{1}[t] = \mathbb{1}\ (mkarr\ t)$

proof –

have $mkarr\ \mathbb{1}[t] = mkarr\ (t \cdot \mathbb{1}[\![Dom\ t]\!])$

using *assms Arr-implies-Ide-Dom Ide-in-Hom Diagonalize-preserves-Ide
Diag-Diagonalize Par-Arr-norm*

by (*intro mkarr-eqI simp-all*)

also have $\dots = mkarr\ t \cdot mkarr\ \mathbb{1}[\![Dom\ t]\!]$

using *assms Arr-implies-Ide-Dom Par-Arr-norm Ide-in-Hom* **by** *simp*

also have $\dots = mkarr\ t \cdot \mathbb{1}[dom\ (mkarr\ t)]$

proof –

have $arr\ \mathbb{1}[mkarr\ (Dom\ t)]$

using *assms Arr-implies-Ide-Dom ide-mkarr-Ide* **by** *simp*

moreover have $\mathbb{1}[\![Dom\ t]\!] \in \mathbb{1}[mkarr\ (Dom\ t)]$

using *assms Arr-implies-Ide-Dom Lunit-in-lunit rep-mkarr
rep-in-arr [of mkarr (Dom t)]*

by *simp*

ultimately show *?thesis*

using *assms mkarr-memb(2)* **by** *simp*

qed

also have $\dots = \mathbb{1}\ (mkarr\ t)$

using *assms Arr-implies-Ide-Dom ide-mkarr-Ide lunit-agreement* **by** *simp*

finally show *?thesis* **by** *blast*

qed

lemma *mkarr-Lunit'*:

assumes $Arr\ t$

shows $mkarr\ \mathbb{1}^{-1}[t] = \mathbb{1}'\ (mkarr\ t)$

proof –

have $mkarr\ \mathbb{1}^{-1}[t] = mkarr\ (\mathbb{1}^{-1}[\![Cod\ t]\!] \cdot t)$

using *assms Arr-implies-Ide-Cod Ide-in-Hom Diagonalize-preserves-Ide
Diag-Diagonalize Par-Arr-norm*

by (*intro mkarr-eqI simp-all*)

also have $\dots = mkarr\ \mathbb{1}^{-1}[\![Cod\ t]\!] \cdot mkarr\ t$

using *assms Arr-implies-Ide-Cod Ide-in-Hom Par-Arr-norm* **by** *simp*

also have $\dots = mkarr\ (Inv\ \mathbb{1}[\![Cod\ t]\!]) \cdot mkarr\ t$

proof –

have $mkarr\ \mathbb{1}^{-1}[\![Cod\ t]\!] = mkarr\ (Inv\ \mathbb{1}[\![Cod\ t]\!])$

using *assms Arr-implies-Ide-Cod Ide-in-Hom Par-Arr-norm Inv-in-Hom
Ide-implies-Can norm-preserves-Can Diagonalize-Inv Diagonalize-preserves-Ide*

by (*intro mkarr-eqI, simp-all*)

thus *?thesis* **by** *argo*

qed

also have $\dots = \mathbb{1}'\ (cod\ (mkarr\ t)) \cdot mkarr\ t$

proof –

have $mkarr\ (Inv\ \mathbb{1}[\![Cod\ t]\!]) \cdot mkarr\ t = lunit'\ (cod\ (mkarr\ t)) \cdot mkarr\ t$

using *assms* *Arr-implies-Ide-Cod rep-mkarr Par-Arr-norm inv-mkarr*
norm-preserves-Can Ide-implies-Can lunit-agreement l'-ide-simp
Can-implies-Arr arr-mkarr cod-mkarr ide-cod lunit_{FMC}-def
by (*metis* (*no-types, lifting*) *Can.simps(5)*)
also have ... = $l'(\text{cod } (mkarr\ t)) \cdot mkarr\ t$
using *assms* *l'-ide-simp arr-mkarr ide-cod* **by** *presburger*
finally show *?thesis* **by** *blast*
qed
also have ... = $l'(mkarr\ t)$
using *assms* *l'.naturality2* [*of mkarr t*] **by** *simp*
finally show *?thesis* **by** *blast*
qed

lemma *mkarr-Runit*:
assumes *Arr t*
shows $mkarr\ r[t] = \varrho(mkarr\ t)$
proof –
have $mkarr\ r[t] = mkarr\ (t \cdot r[\|Dom\ t\|])$
proof –
have $\neg Diag\ (Dom\ t \otimes \mathcal{I})$ **by** (*cases Dom t*) *simp-all*
thus *?thesis*
using *assms* *Par-Arr-norm Arr-implies-Ide-Dom Ide-in-Hom Diag-Diagonalize*
Diagonalize-preserves-Ide
by (*intro mkarr-eqI*) *simp-all*
qed
also have ... = $mkarr\ t \cdot mkarr\ r[\|Dom\ t\|]$
using *assms* *Arr-implies-Ide-Dom Par-Arr-norm Ide-in-Hom* **by** *simp*
also have ... = $mkarr\ t \cdot r[dom\ (mkarr\ t)]$
proof –
have $arr\ r[mkarr\ (Dom\ t)]$
using *assms* *Arr-implies-Ide-Dom ide-mkarr-Ide* **by** *simp*
moreover have $r[\|Dom\ t\|] \in r[mkarr\ (Dom\ t)]$
using *assms* *Arr-implies-Ide-Dom Runit-in-runit rep-mkarr*
rep-in-arr [*of mkarr (Dom t)*]
by *simp*
moreover have $mkarr\ (Dom\ t) = mkarr\ \|Dom\ t\|$
using *assms* *mkarr-rep rep-mkarr arr-mkarr Ide-implies-Arr Arr-implies-Ide-Dom*
by *metis*
ultimately show *?thesis*
using *assms* *mkarr-memb(2)* **by** *simp*
qed
also have ... = $\varrho(mkarr\ t)$
using *assms* *Arr-implies-Ide-Dom ide-mkarr-Ide runit-agreement* **by** *simp*
finally show *?thesis* **by** *blast*
qed

lemma *mkarr-Runit'*:
assumes *Arr t*
shows $mkarr\ r^{-1}[t] = \varrho'(mkarr\ t)$

```

proof –
  have  $mkarr\ r^{-1}[t] = mkarr\ (r^{-1}[\|Cod\ t\|]) \cdot t$ 
  proof –
    have  $\neg\ Diag\ (Cod\ t \otimes \mathcal{I})$  by  $(cases\ Cod\ t)\ simp\text{-all}$ 
    thus ?thesis
    using assms Par-Arr-norm Arr-implies-Ide-Cod Ide-in-Hom
      Diagonalize-preserves-Ide Diag-Diagonalize
    by  $(intro\ mkarr\ eqI)\ simp\text{-all}$ 
  qed
  also have  $\dots = mkarr\ r^{-1}[\|Cod\ t\|] \cdot mkarr\ t$ 
    using assms Arr-implies-Ide-Cod Ide-in-Hom Par-Arr-norm by simp
  also have  $\dots = mkarr\ (Inv\ r[\|Cod\ t\|]) \cdot mkarr\ t$ 
  proof –
    have  $mkarr\ (Runit'\ (norm\ (Cod\ t))) = mkarr\ (Inv\ (Runit\ (norm\ (Cod\ t))))$ 
    using assms Arr-implies-Ide-Cod Ide-in-Hom Par-Arr-norm Inv-in-Hom
      Ide-implies-Can norm-preserves-Can Diagonalize-Inv Diagonalize-preserves-Ide
    by  $(intro\ mkarr\ eqI)\ simp\text{-all}$ 
    thus ?thesis by argo
  qed
  also have  $\dots = \varrho'\ (cod\ (mkarr\ t)) \cdot mkarr\ t$ 
  proof –
    have  $mkarr\ (Inv\ r[\|Cod\ t\|]) \cdot mkarr\ t = runit'\ (cod\ (mkarr\ t)) \cdot mkarr\ t$ 
    using assms Arr-implies-Ide-Cod rep-mkarr inv-mkarr norm-preserves-Can
      Ide-implies-Can runit-agreement Can-implies-Arr arr-mkarr cod-mkarr
      ide-cod runit_FMC-def
    by  $(metis\ (no\text{-types},\ lifting)\ Can.simps(7))$ 
    also have  $\dots = \varrho'\ (cod\ (mkarr\ t)) \cdot mkarr\ t$ 
  proof –
    have  $runit'\ (cod\ (mkarr\ t)) = \varrho'\ (cod\ (mkarr\ t))$ 
    using assms  $\varrho'\text{-ide-simp arr-mkarr ide-cod}$  by blast
    thus ?thesis by argo
  qed
  finally show ?thesis by blast
  qed
  also have  $\dots = \varrho'\ (mkarr\ t)$ 
    using assms  $\varrho'\text{-naturality2 [of mkarr t]}$  by simp
  finally show ?thesis by blast
qed

lemma mkarr-Assoc:
assumes Arr t and Arr u and Arr v
shows  $mkarr\ \mathbf{a}[t, u, v] = \alpha\ (mkarr\ t, mkarr\ u, mkarr\ v)$ 
proof –
  have  $mkarr\ \mathbf{a}[t, u, v] = mkarr\ ((t \otimes u \otimes v) \cdot \mathbf{a}[\|Dom\ t\|, \|Dom\ u\|, \|Dom\ v\|])$ 
  using assms Arr-implies-Ide-Dom Arr-implies-Ide-Cod Ide-in-Hom
    Diag-Diagonalize Diagonalize-preserves-Ide TensorDiag-preserves-Ide
    TensorDiag-preserves-Diag TensorDiag-assoc Par-Arr-norm
  by  $(intro\ mkarr\ eqI, simp\text{-all})$ 
  also have  $\dots = \alpha\ (mkarr\ t, mkarr\ u, mkarr\ v)$ 

```

using *assms Arr-implies-Ide-Dom rep-mkarr Ide-in-Hom assoc_{FM C}-def*
Par-Arr-norm [of Dom t] Par-Arr-norm [of Dom u] Par-Arr-norm [of Dom v]
α-simp
by *simp*
finally show *?thesis* **by** *blast*
qed

lemma *mkarr-Assoc'*:

assumes *Arr t and Arr u and Arr v*

shows *mkarr a⁻¹[t, u, v] = α' (mkarr t, mkarr u, mkarr v)*

proof –

have *mkarr a⁻¹[t, u, v] = mkarr (a⁻¹[|| Cod t||, || Cod u||, || Cod v||] · (t ⊗ u ⊗ v))*

using *assms Par-Arr-norm Arr-implies-Ide-Cod Ide-in-Hom Diag-Diagonalize*

TensorDiag-preserves-Diag CompDiag-Cod-Diag [of [t] [⊗] [u] [⊗] [v]]

by *(intro mkarr-eqI, simp-all)*

also have *... = mkarr a⁻¹[|| Cod t||, || Cod u||, || Cod v||] · mkarr (t ⊗ u ⊗ v)*

using *assms Arr-implies-Ide-Cod Ide-in-Hom Par-Arr-norm* **by** *simp*

also have *... = mkarr (Inv a[|| Cod t||, || Cod u||, || Cod v||]) · mkarr (t ⊗ u ⊗ v)*

proof –

have *mkarr a⁻¹[|| Cod t||, || Cod u||, || Cod v||] =*

mkarr (Inv a[|| Cod t||, || Cod u||, || Cod v||])

using *assms Arr-implies-Ide-Cod Ide-in-Hom Par-Arr-norm Inv-in-Hom Ide-implies-Can*

norm-preserves-Can Diagonalize-Inv Diagonalize-preserves-Ide

by *(intro mkarr-eqI, simp-all)*

thus *?thesis* **by** *argo*

qed

also have *... = inv (mkarr a[|| Cod t||, || Cod u||, || Cod v||]) · mkarr (t ⊗ u ⊗ v)*

using *assms Arr-implies-Ide-Cod Ide-implies-Can norm-preserves-Can* **by** *simp*

also have *... = α' (mkarr t, mkarr u, mkarr v)*

proof –

have *mkarr (a⁻¹[Inv || Cod t||, Inv || Cod u||, Inv || Cod v||] · (Cod t ⊗ Cod u ⊗ Cod v))*

= mkarr a⁻¹[Inv || Cod t||, Inv || Cod u||, Inv || Cod v||]

using *assms Arr-implies-Ide-Cod Inv-in-Hom norm-preserves-Can Diagonalize-Inv*

Ide-implies-Can Diag-Diagonalize Ide-in-Hom Diagonalize-preserves-Ide

Par-Arr-norm TensorDiag-preserves-Diag

CompDiag-Cod-Diag [of [Cod t] [⊗] [Cod u] [⊗] [Cod v]]

by *(intro mkarr-eqI) simp-all*

thus *?thesis*

using *assms Arr-implies-Ide-Cod rep-mkarr assoc_{FM C}-def α'.map-simp* **by** *simp*

qed

finally show *?thesis* **by** *blast*

qed

Next, we define the “inclusion of generators” functor from C to $\mathcal{F}C$.

definition *inclusion-of-generators*

where *inclusion-of-generators* $\equiv \lambda f. \text{if } C.\text{arr } f \text{ then } \text{mkarr } \langle f \rangle \text{ else null}$

lemma *inclusion-is-functor*:

shows *functor C comp inclusion-of-generators*

```

unfolding inclusion-of-generators-def
apply unfold-locales
  apply auto[4]
by (elim C.seqE, simp, intro mkarr-eqI, auto)

```

end

We now show that, given a functor V from C to a monoidal category D , the evaluation map that takes formal arrows of the monoidal language of C to arrows of D induces a strict monoidal functor from $\mathcal{F}C$ to D .

```

locale evaluation-functor =
  C: category C +
  D: monoidal-category D TD αD ιD +
  evaluation-map C D TD αD ιD V +
  FC: free-monoidal-category C
for C :: 'c comp      (infixr <'<C>' 55)
and D :: 'd comp      (infixr <'<D>' 55)
and TD :: 'd * 'd ⇒ 'd
and αD :: 'd * 'd * 'd ⇒ 'd
and ιD :: 'd
and V :: 'c ⇒ 'd
begin

```

```

  notation eval      (<'<{-}>')

```

```

  definition map
  where map f ≡ if FC.arr f then {FC.rep f} else D.null

```

It follows from the coherence theorem that a formal arrow and its normal form always have the same evaluation.

```

lemma eval-norm:
assumes Arr t
shows  $\{\!\|t\|\!\} = \{t\}$ 
  using assms FC.Par-Arr-norm FC.Diagonalize-norm coherence canonical-factorization
  by simp

```

```

interpretation functor FC.comp D map

```

proof

```

  fix f
  show  $\neg FC.arr f \implies map f = D.null$  using map-def by simp
  assume f: FC.arr f
  show D.arr (map f) using f map-def FC.arr-char by simp
  show D.dom (map f) = map (FC.dom f)
    using f map-def eval-norm FC.rep-dom Arr-implies-Ide-Dom by auto
  show D.cod (map f) = map (FC.cod f)
    using f map-def eval-norm FC.rep-cod Arr-implies-Ide-Cod by auto
  next
  fix f g
  assume fg: FC.seq g f

```

show $\text{map } (\mathcal{F}C.\text{comp } g f) = D (\text{map } g) (\text{map } f)$
using $\text{fg map-def } \mathcal{F}C.\text{rep-comp } \mathcal{F}C.\text{rep-preserves-seq eval-norm}$ **by** *auto*
qed

lemma *is-functor*:
shows *functor* $\mathcal{F}C.\text{comp } D \text{ map } ..$

interpretation FF : *product-functor* $\mathcal{F}C.\text{comp } \mathcal{F}C.\text{comp } D D \text{ map } \text{map } ..$
interpretation FoT : *composite-functor* $\mathcal{F}C.CC.\text{comp } \mathcal{F}C.\text{comp } D \mathcal{F}C.T_{FMC} \text{ map } ..$
interpretation $ToFF$: *composite-functor* $\mathcal{F}C.CC.\text{comp } D.CC.\text{comp } D FF.\text{map } T_D ..$

interpretation *strict-monoidal-functor*
 $\mathcal{F}C.\text{comp } \mathcal{F}C.T_{FMC} \mathcal{F}C.\alpha \mathcal{F}C.\iota D T_D \alpha_D \iota_D \text{ map}$

proof

show $\text{map } \mathcal{F}C.\iota = \iota_D$
using $\mathcal{F}C.\iota\text{-def } \mathcal{F}C.\text{lunit-agreement map-def } \mathcal{F}C.\text{rep-lunit } \mathcal{F}C.\text{Arr-rep [of } \mathcal{I}]$
 $\text{eval-norm } \mathcal{F}C.\text{lunit-agreement } D.\text{unit-or-coincidence } D.\text{comp-cod-arr } D.\text{unit-in-hom}$
by *auto*
show $\bigwedge f g. [\mathcal{F}C.\text{arr } f; \mathcal{F}C.\text{arr } g] \implies$
 $\text{map } (\mathcal{F}C.\text{tensor } f g) = D.\text{tensor } (\text{map } f) (\text{map } g)$
using $\text{map-def } \mathcal{F}C.\text{rep-tensor } \mathcal{F}C.\text{Arr-rep eval-norm}$ **by** *simp*
show $\bigwedge a b c. [\mathcal{F}C.\text{ide } a; \mathcal{F}C.\text{ide } b; \mathcal{F}C.\text{ide } c] \implies$
 $\text{map } (\mathcal{F}C.\text{assoc } a b c) = D.\text{assoc } (\text{map } a) (\text{map } b) (\text{map } c)$
using $\text{map-def } \mathcal{F}C.\text{assoc}_{FMC}\text{-def } \mathcal{F}C.\text{rep-mkarr eval-norm}$ **by** *auto*
qed

lemma *is-strict-monoidal-functor*:
shows *strict-monoidal-functor* $\mathcal{F}C.\text{comp } \mathcal{F}C.T_{FMC} \mathcal{F}C.\alpha \mathcal{F}C.\iota D T_D \alpha_D \iota_D \text{ map}$
 $..$

end

sublocale *evaluation-functor* \subseteq *strict-monoidal-functor*
 $\mathcal{F}C.\text{comp } \mathcal{F}C.T_{FMC} \mathcal{F}C.\alpha_{FMC} \mathcal{F}C.\iota_{FMC} D T_D \alpha_D \iota_D \text{ map}$
using *is-strict-monoidal-functor* **by** *auto*

The final step in proving freeness is to show that the evaluation functor is the *unique* strict monoidal extension of the functor V to $\mathcal{F}C$. This is done by induction, exploiting the syntactic construction of $\mathcal{F}C$.

To ease the statement and proof of the result, we define a locale that expresses that F is a strict monoidal extension to monoidal category C , of a functor V from C_0 to a monoidal category D , along a functor I from C_0 to C .

locale *strict-monoidal-extension* =
 C_0 : *category* C_0 +
 C : *monoidal-category* $C T_C \alpha_C \iota_C$ +
 D : *monoidal-category* $D T_D \alpha_D \iota_D$ +
 I : *functor* $C_0 C I$ +
 V : *functor* $C_0 D V$ +

```

    strict-monoidal-functor C T_C α_C ι_C D T_D α_D ι_D F
  for C_0 :: 'c_0 comp
  and C :: 'c comp      (infixr ⟨·_C⟩ 55)
  and T_C :: 'c * 'c ⇒ 'c
  and α_C :: 'c * 'c * 'c ⇒ 'c
  and ι_C :: 'c
  and D :: 'd comp      (infixr ⟨·_D⟩ 55)
  and T_D :: 'd * 'd ⇒ 'd
  and α_D :: 'd * 'd * 'd ⇒ 'd
  and ι_D :: 'd
  and I :: 'c_0 ⇒ 'c
  and V :: 'c_0 ⇒ 'd
  and F :: 'c ⇒ 'd +
  assumes is-extension: ∀ f. C_0.arr f → F (I f) = V f

  sublocale evaluation-functor ⊆
    strict-monoidal-extension C FC.comp FC.T_FMC FC.α FC.ι D T_D α_D ι_D
    FC.inclusion-of-generators V map

  proof –
    interpret inclusion: functor C FC.comp FC.inclusion-of-generators
    using FC.inclusion-is-functor by auto
    show strict-monoidal-extension C FC.comp FC.T_FMC FC.α FC.ι D T_D α_D ι_D
    FC.inclusion-of-generators V map

    apply unfold-locales
    using map-def FC.rep-mkarr eval-norm FC.inclusion-of-generators-def by simp
  qed

```

A special case of interest is a strict monoidal extension to $\mathcal{F}C$, of a functor V from a category C to a monoidal category D , along the inclusion of generators from C to $\mathcal{F}C$. The evaluation functor induced by V is such an extension.

```

  locale strict-monoidal-extension-to-free-monoidal-category =
    C: category C +
    monoidal-language C +
    FC: free-monoidal-category C +
    strict-monoidal-extension C FC.comp FC.T_FMC FC.α FC.ι D T_D α_D ι_D
    FC.inclusion-of-generators V F

  for C :: 'c comp      (infixr ⟨·_C⟩ 55)
  and D :: 'd comp      (infixr ⟨·_D⟩ 55)
  and T_D :: 'd * 'd ⇒ 'd
  and α_D :: 'd * 'd * 'd ⇒ 'd
  and ι_D :: 'd
  and V :: 'c ⇒ 'd
  and F :: 'c free-monoidal-category.arr ⇒ 'd
  begin

    lemma strictly-preserves-everything:
    shows C.arr f ⇒ F (FC.mkarr ⟨f⟩) = V f
    and F (FC.mkarr  $\mathcal{I}$ ) =  $\mathcal{I}_D$ 
    and [ Arr t; Arr u ] ⇒ F (FC.mkarr (t ⊗ u)) = F (FC.mkarr t) ⊗_D F (FC.mkarr u)
  end

```

and $\llbracket \text{Arr } t; \text{Arr } u; \text{Dom } t = \text{Cod } u \rrbracket \implies$
 $F (\mathcal{F}C.\text{mkarr } (t \cdot u)) = F (\mathcal{F}C.\text{mkarr } t) \cdot_D F (\mathcal{F}C.\text{mkarr } u)$
and $\text{Arr } t \implies F (\mathcal{F}C.\text{mkarr } \mathbf{l}[t]) = D.\mathbf{l} (F (\mathcal{F}C.\text{mkarr } t))$
and $\text{Arr } t \implies F (\mathcal{F}C.\text{mkarr } \mathbf{l}^{-1}[t]) = D.\mathbf{l}'.\text{map} (F (\mathcal{F}C.\text{mkarr } t))$
and $\text{Arr } t \implies F (\mathcal{F}C.\text{mkarr } \mathbf{r}[t]) = D.\mathbf{r} (F (\mathcal{F}C.\text{mkarr } t))$
and $\text{Arr } t \implies F (\mathcal{F}C.\text{mkarr } \mathbf{r}^{-1}[t]) = D.\mathbf{r}'.\text{map} (F (\mathcal{F}C.\text{mkarr } t))$
and $\llbracket \text{Arr } t; \text{Arr } u; \text{Arr } v \rrbracket \implies$
 $F (\mathcal{F}C.\text{mkarr } \mathbf{a}[t, u, v]) = \alpha_D (F (\mathcal{F}C.\text{mkarr } t), F (\mathcal{F}C.\text{mkarr } u), F (\mathcal{F}C.\text{mkarr } v))$
and $\llbracket \text{Arr } t; \text{Arr } u; \text{Arr } v \rrbracket \implies$
 $F (\mathcal{F}C.\text{mkarr } \mathbf{a}^{-1}[t, u, v])$
 $= D.\alpha' (F (\mathcal{F}C.\text{mkarr } t), F (\mathcal{F}C.\text{mkarr } u), F (\mathcal{F}C.\text{mkarr } v))$
proof –
show $C.\text{arr } f \implies F (\mathcal{F}C.\text{mkarr } \langle f \rangle) = V f$
using *is-extension* $\mathcal{F}C.\text{inclusion-of-generators-def}$ **by** *simp*
show $F (\mathcal{F}C.\text{mkarr } \mathcal{I}) = \mathcal{I}_D$
using $\mathcal{F}C.\text{mkarr-Unity}$ $\mathcal{F}C.\iota\text{-def}$ *strictly-preserves-unity* $\mathcal{F}C.\mathcal{I}\text{-agreement}$ **by** *auto*
show *tensor-case*:
 $\bigwedge t u. \llbracket \text{Arr } t; \text{Arr } u \rrbracket \implies$
 $F (\mathcal{F}C.\text{mkarr } (t \otimes u)) = F (\mathcal{F}C.\text{mkarr } t) \otimes_D F (\mathcal{F}C.\text{mkarr } u)$
proof –
fix $t u$
assume $t: \text{Arr } t$ **and** $u: \text{Arr } u$
have $F (\mathcal{F}C.\text{mkarr } (t \otimes u)) = F (\mathcal{F}C.\text{tensor } (\mathcal{F}C.\text{mkarr } t) (\mathcal{F}C.\text{mkarr } u))$
using $t u$ $\mathcal{F}C.\text{tensor-mkarr}$ $\mathcal{F}C.\text{arr-mkarr}$ **by** *simp*
also have $\dots = F (\mathcal{F}C.\text{mkarr } t) \otimes_D F (\mathcal{F}C.\text{mkarr } u)$
using $t u$ $\mathcal{F}C.\text{arr-mkarr}$ *strictly-preserves-tensor* **by** *blast*
finally show $F (\mathcal{F}C.\text{mkarr } (t \otimes u)) = F (\mathcal{F}C.\text{mkarr } t) \otimes_D F (\mathcal{F}C.\text{mkarr } u)$
by *fast*
qed
show $\llbracket \text{Arr } t; \text{Arr } u; \text{Dom } t = \text{Cod } u \rrbracket \implies$
 $F (\mathcal{F}C.\text{mkarr } (t \cdot u)) = F (\mathcal{F}C.\text{mkarr } t) \cdot_D F (\mathcal{F}C.\text{mkarr } u)$
proof –
fix $t u$
assume $t: \text{Arr } t$ **and** $u: \text{Arr } u$ **and** $tu: \text{Dom } t = \text{Cod } u$
show $F (\mathcal{F}C.\text{mkarr } (t \cdot u)) = F (\mathcal{F}C.\text{mkarr } t) \cdot_D F (\mathcal{F}C.\text{mkarr } u)$
proof –
have $F (\mathcal{F}C.\text{mkarr } (t \cdot u)) = F (\mathcal{F}C.\text{mkarr } t \cdot \mathcal{F}C.\text{mkarr } u)$
using $t u tu$ $\mathcal{F}C.\text{comp-mkarr}$ **by** *simp*
also have $\dots = F (\mathcal{F}C.\text{mkarr } t) \cdot_D F (\mathcal{F}C.\text{mkarr } u)$
using $t u tu$ $\mathcal{F}C.\text{arr-mkarr}$ **by** *fastforce*
finally show *?thesis* **by** *blast*
qed
qed
show $\text{Arr } t \implies F (\mathcal{F}C.\text{mkarr } \mathbf{l}[t]) = D.\mathbf{l} (F (\mathcal{F}C.\text{mkarr } t))$
using $\mathcal{F}C.\text{mkarr-Lunit}$ *Arr-implies-Ide-Dom* $\mathcal{F}C.\text{ide-mkarr-Ide}$ *strictly-preserves-lunit*
by *simp*
show $\text{Arr } t \implies F (\mathcal{F}C.\text{mkarr } \mathbf{r}[t]) = D.\mathbf{r} (F (\mathcal{F}C.\text{mkarr } t))$
using $\mathcal{F}C.\text{mkarr-Runit}$ *Arr-implies-Ide-Dom* $\mathcal{F}C.\text{ide-mkarr-Ide}$ *strictly-preserves-runit*
by *simp*

show $\llbracket \text{Arr } t; \text{Arr } u; \text{Arr } v \rrbracket \implies$
 $F (\mathcal{F}C.\text{mkarr } \mathbf{a}[t, u, v])$
 $= \alpha_D (F (\mathcal{F}C.\text{mkarr } t), F (\mathcal{F}C.\text{mkarr } u), F (\mathcal{F}C.\text{mkarr } v))$
using $\mathcal{F}C.\text{mkarr-Assoc strictly-preserves-assoc } \mathcal{F}C.\text{ide-mkarr-Ide tensor-case}$
by *simp*
show $\text{Arr } t \implies F (\mathcal{F}C.\text{mkarr } \mathbf{l}^{-1}[t]) = D.\mathbf{l}'.\text{map } (F (\mathcal{F}C.\text{mkarr } t))$
proof –
assume $t: \text{Arr } t$
have $F (\mathcal{F}C.\text{mkarr } \mathbf{l}^{-1}[t]) = F (\mathcal{F}C.\text{lunit}' (\mathcal{F}C.\text{mkarr } (\text{Cod } t))) \cdot_D F (\mathcal{F}C.\text{mkarr } t)$
using $t \mathcal{F}C.\text{mkarr-Lunit}' \text{Arr-implies-Ide-Cod } \mathcal{F}C.\text{ide-mkarr-Ide } \mathcal{F}C.\mathbf{l}'.\text{map-simp}$
 $\mathcal{F}C.\text{comp-cod-arr}$
by *simp*
also have $\dots = D.\text{lunit}' (D.\text{cod } (F (\mathcal{F}C.\text{mkarr } t))) \cdot_D F (\mathcal{F}C.\text{mkarr } t)$
using $t \text{Arr-implies-Ide-Cod } \mathcal{F}C.\text{ide-mkarr-Ide strictly-preserves-lunit}$
 preserves-inv
by *simp*
also have $\dots = D.\mathbf{l}'.\text{map } (F (\mathcal{F}C.\text{mkarr } t))$
using $t D.\mathbf{l}'.\text{map-simp } D.\text{comp-cod-arr}$ **by** *simp*
finally show *?thesis* **by** *blast*
qed
show $\text{Arr } t \implies F (\mathcal{F}C.\text{mkarr } \mathbf{r}^{-1}[t]) = D.\mathbf{r}'.\text{map } (F (\mathcal{F}C.\text{mkarr } t))$
proof –
assume $t: \text{Arr } t$
have $F (\mathcal{F}C.\text{mkarr } \mathbf{r}^{-1}[t]) = F (\mathcal{F}C.\text{runit}' (\mathcal{F}C.\text{mkarr } (\text{Cod } t))) \cdot_D F (\mathcal{F}C.\text{mkarr } t)$
using $t \mathcal{F}C.\text{mkarr-Runit}' \text{Arr-implies-Ide-Cod } \mathcal{F}C.\text{ide-mkarr-Ide } \mathcal{F}C.\mathbf{r}'.\text{map-simp}$
 $\mathcal{F}C.\text{comp-cod-arr}$
by *simp*
also have $\dots = D.\text{runit}' (D.\text{cod } (F (\mathcal{F}C.\text{mkarr } t))) \cdot_D F (\mathcal{F}C.\text{mkarr } t)$
using $t \text{Arr-implies-Ide-Cod } \mathcal{F}C.\text{ide-mkarr-Ide strictly-preserves-runit}$
 preserves-inv
by *simp*
also have $\dots = D.\mathbf{r}'.\text{map } (F (\mathcal{F}C.\text{mkarr } t))$
using $t D.\mathbf{r}'.\text{map-simp } D.\text{comp-cod-arr}$ **by** *simp*
finally show *?thesis* **by** *blast*
qed
show $\llbracket \text{Arr } t; \text{Arr } u; \text{Arr } v \rrbracket \implies$
 $F (\mathcal{F}C.\text{mkarr } \mathbf{a}^{-1}[t, u, v])$
 $= D.\mathbf{a}'.\text{map } (F (\mathcal{F}C.\text{mkarr } t), F (\mathcal{F}C.\text{mkarr } u), F (\mathcal{F}C.\text{mkarr } v))$
proof –
assume $t: \text{Arr } t$ **and** $u: \text{Arr } u$ **and** $v: \text{Arr } v$
have $F (\mathcal{F}C.\text{mkarr } \mathbf{a}^{-1}[t, u, v]) =$
 $F (\mathcal{F}C.\text{assoc}' (\mathcal{F}C.\text{mkarr } (\text{Cod } t)) (\mathcal{F}C.\text{mkarr } (\text{Cod } u)) (\mathcal{F}C.\text{mkarr } (\text{Cod } v))) \cdot_D$
 $(F (\mathcal{F}C.\text{mkarr } t) \otimes_D F (\mathcal{F}C.\text{mkarr } u) \otimes_D F (\mathcal{F}C.\text{mkarr } v))$
using $t u v \mathcal{F}C.\text{mkarr-Assoc}' \text{Arr-implies-Ide-Cod } \mathcal{F}C.\text{ide-mkarr-Ide } \mathcal{F}C.\mathbf{a}'.\text{map-simp}$
 $\text{tensor-case } \mathcal{F}C.\text{iso-assoc}$
by *simp*
also have $\dots = D.\text{assoc}' (D.\text{cod } (F (\mathcal{F}C.\text{mkarr } t))) (D.\text{cod } (F (\mathcal{F}C.\text{mkarr } u)))$
 $(D.\text{cod } (F (\mathcal{F}C.\text{mkarr } v))) \cdot_D$
 $(F (\mathcal{F}C.\text{mkarr } t) \otimes_D F (\mathcal{F}C.\text{mkarr } u) \otimes_D F (\mathcal{F}C.\text{mkarr } v))$


```

    using t u v FC.ide-mkarr-Ide Arr-implies-Ide-Cod preserves-inv FC.iso-assoc
      strictly-preserved-assoc
      [of FC.mkarr (Cod t) FC.mkarr (Cod u) FC.mkarr (Cod v)]
    by simp
    also have ... = D.alpha'.map (F (FC.mkarr t), F (FC.mkarr u), F (FC.mkarr v))
      using t u v D.alpha'.map-simp by simp
    finally show ?thesis by blast
  qed
qed

end

sublocale evaluation-functor  $\subseteq$  strict-monoidal-extension-to-free-monoidal-category
  C D T_D alpha_D l_D V map
..

context free-monoidal-category
begin

  The evaluation functor induced by V is the unique strict monoidal extension of V to
  FC.

  theorem is-free:
  assumes strict-monoidal-extension-to-free-monoidal-category C D T_D alpha_D l_D V F
  shows F = evaluation-functor.map C D T_D alpha_D l_D V
  proof -
    interpret F: strict-monoidal-extension-to-free-monoidal-category C D T_D alpha_D l_D V F
      using assms by auto
    interpret E: evaluation-functor C D T_D alpha_D l_D V ..
    have Ide-case:  $\bigwedge a. Ide\ a \implies F\ (mkarr\ a) = E.map\ (mkarr\ a)$ 
    proof -
      fix a
      show Ide a  $\implies F (mkarr a) = E.map (mkarr a)$ 
        using E.strictly-preserved-everything F.strictly-preserved-everything Ide-implies-Arr
        by (induct a) auto
    qed
    show ?thesis
  proof
    fix f
    have  $\neg arr\ f \implies F\ f = E.map\ f$ 
      using E.extensionality F.extensionality by simp
    moreover have  $arr\ f \implies F\ f = E.map\ f$ 
    proof -
      assume f: arr f
      have Arr (rep f)  $\wedge f = mkarr (rep f)$  using f mkarr-rep by simp
      moreover have  $\bigwedge t. Arr\ t \implies F\ (mkarr\ t) = E.map\ (mkarr\ t)$ 
      proof -
        fix t
        show Arr t  $\implies F (mkarr t) = E.map (mkarr t)$ 
          using Ide-case E.strictly-preserved-everything F.strictly-preserved-everything

```

```

      Arr-implies-Ide-Dom Arr-implies-Ide-Cod
    by (induct t) auto
  qed
  ultimately show  $F f = E.map f$  by metis
  qed
  ultimately show  $F f = E.map f$  by blast
  qed
  qed
end

```

4.3 Strict Subcategory

```

context free-monoidal-category
begin

```

In this section we show that $\mathcal{F}C$ is monoidally equivalent to its full subcategory $\mathcal{F}_S C$ whose objects are the equivalence classes of diagonal identity terms, and that this subcategory is the free strict monoidal category generated by C .

```

interpretation  $\mathcal{F}_S C$ : full-subcategory comp  $\langle \lambda f. ide f \wedge Diag (DOM f) \rangle$ 
  by (unfold-locales) auto

```

The mapping defined on equivalence classes by diagonalizing their representatives is a functor from the free monoidal category to the subcategory $\mathcal{F}_S C$.

```

definition  $D$ 
  where  $D \equiv \lambda f. if\ arr\ f\ then\ mkarr\ [rep\ f]\ else\ \mathcal{F}_S C.null$ 

```

The arrows of $\mathcal{F}_S C$ are those equivalence classes whose canonical representative term has diagonal formal domain and codomain.

```

lemma strict-arr-char:
shows  $\mathcal{F}_S C.arr\ f \longleftrightarrow arr\ f \wedge Diag\ (DOM\ f) \wedge Diag\ (COD\ f)$ 
proof
  show  $arr\ f \wedge Diag\ (DOM\ f) \wedge Diag\ (COD\ f) \implies \mathcal{F}_S C.arr\ f$ 
    using  $\mathcal{F}_S C.arr-char_{SbC}\ DOM-dom\ DOM-cod$  by simp
  show  $\mathcal{F}_S C.arr\ f \implies arr\ f \wedge Diag\ (DOM\ f) \wedge Diag\ (COD\ f)$ 
    using  $\mathcal{F}_S C.arr-char_{SbC}\ Arr-rep\ Arr-implies-Ide-Cod\ Ide-implies-Arr\ DOM-dom\ DOM-cod$ 
    by force
qed

```

Alternatively, the arrows of $\mathcal{F}_S C$ are those equivalence classes that are preserved by diagonalization of representatives.

```

lemma strict-arr-char':
shows  $\mathcal{F}_S C.arr\ f \longleftrightarrow arr\ f \wedge D\ f = f$ 
proof
  fix  $f$ 
  assume  $f: \mathcal{F}_S C.arr\ f$ 
  show  $arr\ f \wedge D\ f = f$ 
proof

```

```

show arr f using f  $\mathcal{F}_S C$ .arr-charSbC by blast
show D f = f
  using f strict-arr-char mkarr-Diagonalize-rep D-def by simp
qed
next
assume f: arr f  $\wedge$  D f = f
show  $\mathcal{F}_S C$ .arr f
proof -
  have arr f using f by simp
  moreover have Diag (DOM f)
  proof -
    have DOM f = DOM (mkarr [rep f]) using f D-def by auto
    also have ... = Dom ||[rep f]||
      using f Arr-rep Diagonalize-in-Hom rep-mkarr by simp
    also have ... = Dom [rep f]
      using f Arr-rep Diagonalize-in-Hom Par-Arr-norm [of [rep f]] by force
    finally have DOM f = Dom [rep f] by blast
    thus ?thesis using f Arr-rep Diag-Diagonalize Dom-preserves-Diag by metis
  qed
  moreover have Diag (COD f)
  proof -
    have COD f = COD (mkarr [rep f]) using f D-def by auto
    also have ... = Cod ||[rep f]||
      using f Arr-rep Diagonalize-in-Hom rep-mkarr by simp
    also have ... = Cod [rep f]
      using f Arr-rep Diagonalize-in-Hom Par-Arr-norm [of [rep f]] by force
    finally have COD f = Cod [rep f] by blast
    thus ?thesis using f Arr-rep Diag-Diagonalize Cod-preserves-Diag by metis
  qed
  ultimately show ?thesis using strict-arr-char by auto
qed
qed

```

interpretation D: functor comp $\mathcal{F}_S C$.comp D

```

proof -
  have 1:  $\bigwedge f. \text{arr } f \implies \mathcal{F}_S C.\text{arr } (D f)$ 
    unfolding strict-arr-char D-def
    using arr-mkarr Diagonalize-in-Hom Arr-rep rep-mkarr Par-Arr-norm
      Arr-implies-Ide-Dom Arr-implies-Ide-Cod Diag-Diagonalize
    by force
  show functor comp  $\mathcal{F}_S C$ .comp D
  proof
    show  $\bigwedge f. \neg \text{arr } f \implies D f = \mathcal{F}_S C.\text{null}$  using D-def by simp
    show  $\bigwedge f. \text{arr } f \implies \mathcal{F}_S C.\text{arr } (D f)$  by fact
    show  $\bigwedge f. \text{arr } f \implies \mathcal{F}_S C.\text{dom } (D f) = D (\text{dom } f)$ 
      using D-def Diagonalize-in-Hom  $\mathcal{F}_S C$ .dom-charSbC  $\mathcal{F}_S C$ .arr-charSbC
        rep-mkarr rep-dom Arr-implies-Ide-Dom Arr-implies-Ide-Cod
        Diagonalize-preserves-Ide ide-mkarr-Ide Diag-Diagonalize Dom-norm
      by simp
  qed

```

```

show 2:  $\bigwedge f. \text{arr } f \implies \mathcal{F}_S C. \text{cod } (D f) = D (\text{cod } f)$ 
  using D-def Diagonalize-in-Hom  $\mathcal{F}_S C. \text{cod-char}_{SbC}$   $\mathcal{F}_S C. \text{arr-char}_{SbC}$ 
    rep-mkarr rep-cod Arr-implies-Ide-Dom Arr-implies-Ide-Cod
    Diagonalize-preserves-Ide ide-mkarr-Ide Diag-Diagonalize Dom-norm
  by simp
fix f g
assume fg: seq g f
hence fg':  $\text{arr } f \wedge \text{arr } g \wedge \text{dom } g = \text{cod } f$  by blast
show  $D (g \cdot f) = \mathcal{F}_S C. \text{comp } (D g) (D f)$ 
proof –
  have seq:  $\mathcal{F}_S C. \text{seq } (\text{mkarr } [\text{rep } g]) (\text{mkarr } [\text{rep } f])$ 
  proof –
    have 3:  $\mathcal{F}_S C. \text{arr } (\text{mkarr } [\text{rep } g]) \wedge \mathcal{F}_S C. \text{arr } (\text{mkarr } [\text{rep } f])$ 
    using fg' 1 arr-char D-def by force
    moreover have  $\mathcal{F}_S C. \text{dom } (\text{mkarr } [\text{rep } g]) = \mathcal{F}_S C. \text{cod } (\text{mkarr } [\text{rep } f])$ 
    using fg' 2 3  $\mathcal{F}_S C. \text{dom-char}_{SbC}$  rep-in-Hom mkarr-in-hom D-def
    Dom-Diagonalize-rep Diag-implies-Arr Diag-Diagonalize(1)  $\mathcal{F}_S C. \text{arr-char}_{SbC}$ 
    by force
    ultimately show ?thesis using  $\mathcal{F}_S C. \text{seqI}$  by auto
  qed
have  $\text{mkarr } [\text{rep } (g \cdot f)] = \mathcal{F}_S C. \text{comp } (\text{mkarr } [\text{rep } g]) (\text{mkarr } [\text{rep } f])$ 
proof –
  have Seq:  $\text{Seq } [\text{rep } g] [\text{rep } f]$ 
  using fg rep-preserves-seq Diagonalize-in-Hom by force
hence 4:  $[\text{rep } g] \cdot [\text{rep } f] \in \text{Hom } [DOM f] [COD g]$ 
  using fg' Seq Diagonalize-in-Hom by auto
have  $\mathcal{F}_S C. \text{comp } (\text{mkarr } [\text{rep } g]) (\text{mkarr } [\text{rep } f]) = \text{mkarr } [\text{rep } g] \cdot \text{mkarr } [\text{rep } f]$ 
  using seq  $\mathcal{F}_S C. \text{comp-char}$   $\mathcal{F}_S C. \text{seq-char}_{SbC}$  by meson
also have  $\dots = \text{mkarr } ([\text{rep } g] \cdot [\text{rep } f])$ 
  using Seq comp-mkarr by fastforce
also have  $\dots = \text{mkarr } [\text{rep } (g \cdot f)]$ 
proof (intro mkarr-eqI)
  show  $\text{Par } ([\text{rep } g] \cdot [\text{rep } f]) [\text{rep } (g \cdot f)]$ 
  using fg 4 rep-in-Hom rep-preserves-seq rep-in-Hom Diagonalize-in-Hom
  Par-Arr-norm
  apply (elim seqE, auto)
  by (simp-all add: rep-comp)
show  $[[\text{rep } g] \cdot [\text{rep } f]] = [[\text{rep } (g \cdot f)]]$ 
  using fg rep-preserves-seq norm-in-Hom Diag-Diagonalize Diagonalize-Diag
  apply auto
  by (simp add: rep-comp)
qed
finally show ?thesis by blast
qed
thus ?thesis using fg D-def by auto
qed
qed
qed

```

lemma *diagonalize-is-functor*:
shows *functor comp* $\mathcal{F}_S C.comp D ..$

lemma *diagonalize-strict-arr*:
assumes $\mathcal{F}_S C.arr f$
shows $D f = f$
using *assms arr-char D-def strict-arr-char Arr-rep Arr-implies-Ide-Dom Ide-implies-Arr*
mkarr-Diagonalize-rep [of f]
by *auto*

lemma *diagonalize-is-idempotent*:
shows $D o D = D$
unfolding *D-def*
using *D.extensionality* $\mathcal{F}_S C.null-char Arr-rep Diagonalize-in-Hom mkarr-Diagonalize-rep$
strict-arr-char rep-mkarr
by *fastforce*

lemma *diagonalize-tensor*:
assumes *arr f and arr g*
shows $D (f \otimes g) = D (D f \otimes D g)$
unfolding *D-def*
using *assms strict-arr-char rep-in-Hom Diagonalize-in-Hom tensor-mkarr rep-tensor*
Diagonalize-in-Hom rep-mkarr Diagonalize-norm Diagonalize-Tensor
by *force*

lemma *ide-diagonalize-can*:
assumes *can f*
shows *ide (D f)*
using *assms D-def Can-rep-can Ide-Diagonalize-Can ide-mkarr-Ide can-implies-arr*
by *simp*

We next show that the diagonalization functor and the inclusion of the full subcategory $\mathcal{F}_S C$ underlie an equivalence of categories. The arrows $mkarr (DOM a \downarrow)$, determined by reductions of canonical representatives, are the components of a natural isomorphism.

interpretation *S*: *full-inclusion-functor comp* $\langle \lambda f. ide f \wedge Diag (DOM f) \rangle ..$
interpretation *DoS*: *composite-functor* $\mathcal{F}_S C.comp comp \mathcal{F}_S C.comp \mathcal{F}_S C.map D$
..
interpretation *SoD*: *composite-functor comp* $\mathcal{F}_S C.comp comp D \mathcal{F}_S C.map ..$

interpretation *v*: *transformation-by-components*
 $comp comp map SoD.map \langle \lambda a. mkarr (DOM a \downarrow) \rangle$

proof

fix *a*

assume *a: ide a*

show $\langle mkarr (DOM a \downarrow) : map a \rightarrow SoD.map a \rangle$

proof –

have $\langle mkarr (DOM a \downarrow) : a \rightarrow mkarr [DOM a] \rangle$

using *a Arr-implies-Ide-Dom red-in-Hom dom-char [of a]* **by** *auto*

```

moreover have map a = a
  using a map-simp by simp
moreover have SoD.map a = mkarr [DOM a]
  using a D.preserves-ide  $\mathcal{F}_S C.ideD$   $\mathcal{F}_S C.map-simp$  D-def Ide-Diagonalize-rep-ide
    Ide-in-Hom Diagonalize-in-Hom
  by force
ultimately show ?thesis by simp
qed
next
fix f
assume f: arr f
show mkarr (DOM (cod f)↓) · map f = SoD.map f · mkarr (DOM (dom f)↓)
proof –
  have SoD.map f · mkarr (DOM (dom f)↓) = mkarr [rep f] · mkarr (DOM f↓)
    using f DOM-dom D.preserves-arr  $\mathcal{F}_S C.map-simp$  D-def by simp
  also have ... = mkarr ([rep f] · DOM f↓)
    using f Diagonalize-in-Hom red-in-Hom comp-mkarr Arr-implies-Ide-Dom
    by simp
  also have ... = mkarr (COD f↓ · rep f)
proof (intro mkarr-eqI)
  show Par ([rep f] · DOM f↓) (COD f↓ · rep f)
    using f Diagonalize-in-Hom red-in-Hom Arr-implies-Ide-Dom Arr-implies-Ide-Cod
    by simp
  show [[rep f] · DOM f↓] = [COD f↓ · rep f]
proof –
  have [[rep f] · DOM f↓] = [rep f] [·] [DOM f↓]
    using f by simp
  also have ... = [rep f]
    using f Arr-implies-Ide-Dom Can-red Ide-Diagonalize-Can [of DOM f↓]
      Diag-Diagonalize CompDiag-Diag-Ide
    by force
  also have ... = [COD f↓] [·] [rep f]
    using f Arr-implies-Ide-Cod Can-red Ide-Diagonalize-Can [of COD f↓]
      Diag-Diagonalize CompDiag-Diag-Ide
    by force
  also have ... = [COD f↓ · rep f]
    by simp
  finally show ?thesis by blast
qed
qed
also have ... = mkarr (COD f↓) · mkarr (rep f)
  using f comp-mkarr rep-in-Hom red-in-Hom Arr-implies-Ide-Cod by blast
also have ... = mkarr (DOM (cod f)↓) · map f
  using f DOM-cod by simp
finally show ?thesis by blast
qed
qed

```

interpretation ν : natural-isomorphism comp comp map SoD.map ν .map

apply *unfold-locales*
using ν .map-simp-ide rep-in-Hom Arr-implies-Ide-Dom Can-red can-mkarr-Can iso-can
by *simp*

The restriction of the diagonalization functor to the subcategory $\mathcal{F}_S C$ is the identity.

lemma *DoS-eq- $\mathcal{F}_S C$* :

shows $DoS.map = \mathcal{F}_S C.map$

proof

fix f

have $\neg \mathcal{F}_S C.arr f \implies DoS.map f = \mathcal{F}_S C.map f$

using *DoS.extensionality $\mathcal{F}_S C.map$ -def* **by** *simp*

moreover have $\mathcal{F}_S C.arr f \implies DoS.map f = \mathcal{F}_S C.map f$

using *$\mathcal{F}_S C.map$ -simp strict-arr-char Diagonalize-Diag D-def mkarr-Diagonalize-rep*

by *simp*

ultimately show $DoS.map f = \mathcal{F}_S C.map f$ **by** *blast*

qed

interpretation μ : *transformation-by-components*

$\mathcal{F}_S C.comp \mathcal{F}_S C.comp DoS.map \mathcal{F}_S C.map \langle \lambda a. a \rangle$

using *$\mathcal{F}_S C.ideD \mathcal{F}_S C.map$ -simp DoS-eq- $\mathcal{F}_S C \mathcal{F}_S C.map$ -simp $\mathcal{F}_S C.comp$ -cod-arr $\mathcal{F}_S C.comp$ -arr-dom*

apply *unfold-locales*

by (*intro $\mathcal{F}_S C.in$ -homI*) *auto*

interpretation μ : *natural-isomorphism $\mathcal{F}_S C.comp \mathcal{F}_S C.comp DoS.map \mathcal{F}_S C.map \mu.map$*

apply *unfold-locales* **using** $\mu.map$ -simp-ide *$\mathcal{F}_S C.ide$ -is-iso* **by** *simp*

interpretation *equivalence-of-categories $\mathcal{F}_S C.comp comp D \mathcal{F}_S C.map \nu.map \mu.map ..$*

We defined the natural isomorphisms μ and ν by giving their components (*i.e.* their values at objects). However, it is helpful in exporting these facts to have simple characterizations of their values for all arrows.

definition μ

where $\mu \equiv \lambda f. \text{if } \mathcal{F}_S C.arr f \text{ then } f \text{ else } \mathcal{F}_S C.null$

definition ν

where $\nu \equiv \lambda f. \text{if } arr f \text{ then } mkarr (COD \downarrow) \cdot f \text{ else } null$

lemma *μ -char*:

shows $\mu.map = \mu$

proof (*intro natural-transformation-eqI*)

show *natural-transformation $\mathcal{F}_S C.comp \mathcal{F}_S C.comp DoS.map \mathcal{F}_S C.map \mu.map ..$*

have *natural-transformation $\mathcal{F}_S C.comp \mathcal{F}_S C.comp \mathcal{F}_S C.map \mathcal{F}_S C.map \mathcal{F}_S C.map$*

using *DoS.as-nat-trans.natural-transformation-axioms DoS-eq- $\mathcal{F}_S C$* **by** *simp*

moreover have $\mathcal{F}_S C.map = \mu$ **unfolding** μ -def **using** *$\mathcal{F}_S C.map$ -def* **by** *blast*

ultimately show *natural-transformation $\mathcal{F}_S C.comp \mathcal{F}_S C.comp DoS.map \mathcal{F}_S C.map \mu$*

using *$\mathcal{F}_S C.as$ -nat-trans.natural-transformation-axioms DoS-eq- $\mathcal{F}_S C$* **by** *simp*

show $\bigwedge a. \mathcal{F}_S C.ide a \implies \mu.map a = \mu a$

using $\mu.map$ -simp-ide *$\mathcal{F}_S C.ideD \mu$ -def* **by** *simp*

qed

lemma *ν -char*:
shows $\nu.map = \nu$
unfolding $\nu.map-def$ $\nu-def$ **using** *map-simp* *DOM-cod* **by** *fastforce*

lemma *is-equivalent-to-strict-subcategory*:
shows *equivalence-of-categories* $\mathcal{F}_S C.comp$ $comp$ D $\mathcal{F}_S C.map$ ν μ
proof –
have *equivalence-of-categories* $\mathcal{F}_S C.comp$ $comp$ D $\mathcal{F}_S C.map$ $\nu.map$ $\mu.map$..
thus *equivalence-of-categories* $\mathcal{F}_S C.comp$ $comp$ D $\mathcal{F}_S C.map$ ν μ
using *ν -char* *μ -char* **by** *simp*
qed

The inclusion of generators functor from C to $\mathcal{F}C$ corestricts to a functor from C to $\mathcal{F}_S C$.

interpretation *I*: *functor* C *comp* *inclusion-of-generators*
using *inclusion-is-functor* **by** *auto*
interpretation *DoI*: *composite-functor* C *comp* $\mathcal{F}_S C.comp$ *inclusion-of-generators* D ..

lemma *DoI-eq-I*:
shows $DoI.map = inclusion-of-generators$
proof
fix f
have $\neg C.arr\ f \implies DoI.map\ f = inclusion-of-generators\ f$
using *DoI.extensionality* *I.extensionality* *$\mathcal{F}_S C.null-char$* **by** *blast*
moreover **have** $C.arr\ f \implies DoI.map\ f = inclusion-of-generators\ f$
proof –
assume $f: C.arr\ f$
have $DoI.map\ f = D\ (inclusion-of-generators\ f)$ **using** f **by** *simp*
also **have** $\dots = inclusion-of-generators\ f$
proof –
have $\mathcal{F}_S C.arr\ (inclusion-of-generators\ f)$
using f *arr-mkarr* *rep-mkarr* *Par-Arr-norm* [*of* $\langle f \rangle$] *strict-arr-char*
inclusion-of-generators-def
by *simp*
thus *?thesis* **using** f *strict-arr-char'* **by** *blast*
qed
finally **show** $DoI.map\ f = inclusion-of-generators\ f$ **by** *blast*
qed
ultimately **show** $DoI.map\ f = inclusion-of-generators\ f$ **by** *blast*
qed

end

Next, we show that the subcategory $\mathcal{F}_S C$ inherits monoidal structure from the ambient category $\mathcal{F}C$, and that this monoidal structure is strict.

locale *free-strict-monoidal-category* =
monoidal-language C +
 $\mathcal{F}C$: *free-monoidal-category* C +

full-subcategory $\mathcal{F}C.comp \lambda f. \mathcal{F}C.ide f \wedge Diag (\mathcal{F}C.DOM f)$
for $C :: 'c \text{ comp}$
begin

interpretation D : *functor* $\mathcal{F}C.comp \text{ comp } \mathcal{F}C.D$
using $\mathcal{F}C.diagonalize-is-functor$ **by** *auto*

notation $comp$ (**infixr** $\langle \cdot_S \rangle$ 55)

definition $tensor_S$ (**infixr** $\langle \otimes_S \rangle$ 53)
where $f \otimes_S g \equiv \mathcal{F}C.D (\mathcal{F}C.tensor f g)$

definition $assoc_S$ ($\langle a_S[-, -, -] \rangle$)
where $assoc_S a b c \equiv a \otimes_S b \otimes_S c$

lemma *tensor-char*:
assumes $arr f$ **and** $arr g$
shows $f \otimes_S g = \mathcal{F}C.mkarr ([\mathcal{F}C.rep f] [\otimes] [\mathcal{F}C.rep g])$
unfolding $\mathcal{F}C.D-def \text{ tensor}_S-def$
using $assms \text{ arr-char}_{SbC} \mathcal{F}C.rep-tensor$ **by** *simp*

lemma *tensor-in-hom* [*simp*]:
assumes $\langle f : a \rightarrow b \rangle$ **and** $\langle g : c \rightarrow d \rangle$
shows $\langle f \otimes_S g : a \otimes_S c \rightarrow b \otimes_S d \rangle$
unfolding $tensor_S-def$
using $assms D.preserves-hom \text{ arr-char}_{SbC} \text{ in-hom-char}_{SbC}$
by (*metis (no-types, lifting) \mathcal{F}C.T-simp \mathcal{F}C.tensor-in-hom in-homE*)

lemma *arr-tensor* [*simp*]:
assumes $arr f$ **and** $arr g$
shows $arr (f \otimes_S g)$
using $assms \text{ arr-iff-in-hom} [of f] \text{ arr-iff-in-hom} [of g] \text{ tensor-in-hom}$ **by** *blast*

lemma *dom-tensor* [*simp*]:
assumes $arr f$ **and** $arr g$
shows $dom (f \otimes_S g) = dom f \otimes_S dom g$
using $assms \text{ arr-iff-in-hom} [of f] \text{ arr-iff-in-hom} [of g] \text{ tensor-in-hom}$ **by** *blast*

lemma *cod-tensor* [*simp*]:
assumes $arr f$ **and** $arr g$
shows $cod (f \otimes_S g) = cod f \otimes_S cod g$
using $assms \text{ arr-iff-in-hom} [of f] \text{ arr-iff-in-hom} [of g] \text{ tensor-in-hom}$ **by** *blast*

lemma *tensor-preserves-ide*:
assumes $ide a$ **and** $ide b$
shows $ide (a \otimes_S b)$
using $assms \text{ tensor}_S-def D.preserves-ide \mathcal{F}C.tensor-preserves-ide \text{ ide-char}_{SbC}$
by *fastforce*

lemma *tensor-tensor*:

assumes *arr f and arr g and arr h*

shows $(f \otimes_S g) \otimes_S h = \mathcal{F}C.mkarr ([\mathcal{F}C.rep\ f] [\otimes] [\mathcal{F}C.rep\ g] [\otimes] [\mathcal{F}C.rep\ h])$

and $f \otimes_S g \otimes_S h = \mathcal{F}C.mkarr ([\mathcal{F}C.rep\ f] [\otimes] [\mathcal{F}C.rep\ g] [\otimes] [\mathcal{F}C.rep\ h])$

proof –

show $(f \otimes_S g) \otimes_S h = \mathcal{F}C.mkarr ([\mathcal{F}C.rep\ f] [\otimes] [\mathcal{F}C.rep\ g] [\otimes] [\mathcal{F}C.rep\ h])$

proof –

have $(f \otimes_S g) \otimes_S h = \mathcal{F}C.mkarr ([\mathcal{F}C.rep\ (f \otimes_S g)] [\otimes] [\mathcal{F}C.rep\ h])$

using *assms Diag-Diagonalize TensorDiag-preserves-Diag Diag-implies-Arr*
FC.COD-mkarr FC.DOM-mkarr FC.strict-arr-char tensor-char

by *simp*

also have

$\dots = \mathcal{F}C.mkarr ([\mathcal{F}C.rep\ (\mathcal{F}C.mkarr ([\mathcal{F}C.rep\ f] [\otimes] [\mathcal{F}C.rep\ g]))] [\otimes] [\mathcal{F}C.rep\ h])$

using *assms arr-char_{SbC} tensor-char* **by** *simp*

also have $\dots = \mathcal{F}C.mkarr ([[\mathcal{F}C.rep\ f] [\otimes] [\mathcal{F}C.rep\ g]] [\otimes] [\mathcal{F}C.rep\ h])$

using *assms FC.rep-mkarr TensorDiag-in-Hom Diag-Diagonalize*
TensorDiag-preserves-Diag arr-char_{SbC}

by *force*

also have $\dots = \mathcal{F}C.mkarr ([\mathcal{F}C.rep\ f] [\otimes] [\mathcal{F}C.rep\ g] [\otimes] [\mathcal{F}C.rep\ h])$

using *assms Diag-Diagonalize TensorDiag-preserves-Diag TensorDiag-assoc arr-char_{SbC}*

by *force*

finally show *?thesis* **by** *blast*

qed

show $f \otimes_S g \otimes_S h = \mathcal{F}C.mkarr ([\mathcal{F}C.rep\ f] [\otimes] [\mathcal{F}C.rep\ g] [\otimes] [\mathcal{F}C.rep\ h])$

proof –

have $\dots = \mathcal{F}C.mkarr ([\mathcal{F}C.rep\ f] [\otimes] [[[\mathcal{F}C.rep\ g] [\otimes] [\mathcal{F}C.rep\ h]]])$

using *assms Diag-Diagonalize TensorDiag-preserves-Diag arr-char_{SbC}* **by** *force*

also have $\dots = \mathcal{F}C.mkarr ([\mathcal{F}C.rep\ f] [\otimes] ([\mathcal{F}C.rep\ (\mathcal{F}C.mkarr ([\mathcal{F}C.rep\ g] [\otimes] [\mathcal{F}C.rep\ h]))])$

$([\mathcal{F}C.rep\ (\mathcal{F}C.mkarr ([\mathcal{F}C.rep\ g] [\otimes] [\mathcal{F}C.rep\ h]))])$

using *assms FC.rep-mkarr TensorDiag-in-Hom Diag-Diagonalize arr-char_{SbC}* **by** *force*

also have $\dots = \mathcal{F}C.mkarr ([\mathcal{F}C.rep\ f] [\otimes] [\mathcal{F}C.rep\ (g \otimes_S h)])$

using *assms tensor-char* **by** *simp*

also have $\dots = f \otimes_S g \otimes_S h$

using *assms Diag-Diagonalize TensorDiag-preserves-Diag Diag-implies-Arr*
FC.COD-mkarr FC.DOM-mkarr FC.strict-arr-char tensor-char

by *simp*

finally show *?thesis* **by** *blast*

qed

qed

lemma *tensor-assoc*:

assumes *arr f and arr g and arr h*

shows $(f \otimes_S g) \otimes_S h = f \otimes_S g \otimes_S h$

using *assms tensor-tensor* **by** *presburger*

lemma *arr-unity*:

shows *arr I*

using *FC.rep-unity FC.Par-Arr-norm FC.I-agreement FC.strict-arr-char* **by** *force*

lemma *tensor-unity-arr*:
assumes *arr f*
shows $\mathcal{I} \otimes_S f = f$
using *assms arr-unity tensor-char FC.strict-arr-char FC.mkarr-Diagonalize-rep*
by *simp*

lemma *tensor-arr-unity*:
assumes *arr f*
shows $f \otimes_S \mathcal{I} = f$
using *assms arr-unity tensor-char FC.strict-arr-char FC.mkarr-Diagonalize-rep*
by *simp*

lemma *assoc-char*:
assumes *ide a and ide b and ide c*
shows $a_S[a, b, c] = \mathcal{F}C.mkarr ([\mathcal{F}C.rep\ a] [\otimes] [\mathcal{F}C.rep\ b] [\otimes] [\mathcal{F}C.rep\ c])$
using *assms tensor-tensor(2) assoc_S-def ideD(1)* **by** *simp*

lemma *assoc-in-hom*:
assumes *ide a and ide b and ide c*
shows $\langle a_S[a, b, c] : (a \otimes_S b) \otimes_S c \rightarrow a \otimes_S b \otimes_S c \rangle$
using *assms tensor-preserves-ide ideD tensor-assoc assoc_S-def*
by (*metis (no-types, lifting) ide-in-hom*)

The category $\mathcal{F}_S C$ is a monoidal category.

interpretation *EMC*: *elementary-monoidal-category comp tensor_S I* $\langle \lambda a. a \rangle \langle \lambda a. a \rangle$ *assoc_S*
proof

show *ide I*
using *ide-char_SbC arr-char_SbC FC.rep-mkarr FC.Dom-norm FC.Cod-norm FC.I-agreement*
by *auto*
show $\bigwedge a. \text{ide } a \implies \text{iso } a$
using *ide-char_SbC arr-char_SbC iso-char_SbC* **by** *auto*
show $\bigwedge f\ a\ b\ g\ c\ d. [\text{in-hom } a\ b\ f; \text{in-hom } c\ d\ g] \implies \text{in-hom } (a \otimes_S c)\ (b \otimes_S d)\ (f \otimes_S g)$
using *tensor-in-hom* **by** *blast*
show $\bigwedge a\ b. [\text{ide } a; \text{ide } b] \implies \text{ide } (a \otimes_S b)$
using *tensor-preserves-ide* **by** *blast*
show $\bigwedge a\ b\ c. [\text{ide } a; \text{ide } b; \text{ide } c] \implies \text{iso } a_S[a, b, c]$
using *tensor-preserves-ide ide-is-iso assoc_S-def* **by** *presburger*
show $\bigwedge a\ b\ c. [\text{ide } a; \text{ide } b; \text{ide } c] \implies \langle a_S[a, b, c] : (a \otimes_S b) \otimes_S c \rightarrow a \otimes_S b \otimes_S c \rangle$
using *assoc-in-hom* **by** *blast*
show $\bigwedge a\ b. [\text{ide } a; \text{ide } b] \implies (a \otimes_S b) \cdot_S a_S[a, \mathcal{I}, b] = a \otimes_S b$
using *ide-def tensor-unity-arr assoc_S-def ideD(1) tensor-preserves-ide comp-ide-self*
by *simp*
show $\bigwedge f. \text{arr } f \implies \text{cod } f \cdot_S (\mathcal{I} \otimes_S f) = f \cdot_S \text{dom } f$
using *tensor-unity-arr comp-arr-dom comp-cod-arr* **by** *presburger*
show $\bigwedge f. \text{arr } f \implies \text{cod } f \cdot_S (f \otimes_S \mathcal{I}) = f \cdot_S \text{dom } f$
using *tensor-arr-unity comp-arr-dom comp-cod-arr* **by** *presburger*
next
fix *a*

```

assume  $a$ : ide  $a$ 
show  $\langle\langle a : \mathcal{I} \otimes_S a \rightarrow a \rangle\rangle$ 
  using  $a$  tensor-unity-arr ide-in-hom [of a] by fast
show  $\langle\langle a : a \otimes_S \mathcal{I} \rightarrow a \rangle\rangle$ 
  using  $a$  tensor-arr-unity ide-in-hom [of a] by fast
next
fix  $f g f' g'$ 
assume  $fg$ : seq  $g f$ 
assume  $fg'$ : seq  $g' f'$ 
show  $(g \otimes_S g') \cdot_S (f \otimes_S f') = g \cdot_S f \otimes_S g' \cdot_S f'$ 
proof –
  have  $A$ :  $\mathcal{F}C.seq\ g\ f$  and  $B$ :  $\mathcal{F}C.seq\ g'\ f'$ 
    using  $fg\ fg'$  seq-charSbC by auto
  have  $(g \otimes_S g') \cdot_S (f \otimes_S f') = \mathcal{F}C.D\ ((g \otimes_S g') \cdot (f \otimes_S f'))$ 
    using  $A\ B$  tensorS-def by fastforce
  also have  $\dots = \mathcal{F}C.D\ (g \cdot f \otimes_S g' \cdot f')$ 
    using  $A\ B\ \mathcal{F}C.interchange\ \mathcal{F}C.T-simp\ \mathcal{F}C.seqE$  by metis
  also have  $\dots = \mathcal{F}C.D\ (g \cdot f) \otimes_S \mathcal{F}C.D\ (g' \cdot f')$ 
    using  $A\ B\ tensorS-def\ \mathcal{F}C.T-simp\ \mathcal{F}C.seqE\ \mathcal{F}C.diagonalize-tensor\ arr-charSbC$ 
    by (metis (no-types, lifting) D.preserves-reflects-arr)
  also have  $\dots = \mathcal{F}C.D\ g \cdot_S \mathcal{F}C.D\ f \otimes_S \mathcal{F}C.D\ g' \cdot_S \mathcal{F}C.D\ f'$ 
    using  $A\ B$  by simp
  also have  $\dots = g \cdot_S f \otimes_S g' \cdot_S f'$ 
    using  $fg\ fg'\ \mathcal{F}C.diagonalize-strict-arr$  by (elim seqE, simp)
  finally show ?thesis by blast
qed
next
fix  $f0\ f1\ f2$ 
assume  $f0$ : arr  $f0$  and  $f1$ : arr  $f1$  and  $f2$ : arr  $f2$ 
show  $a_S[cod\ f0,\ cod\ f1,\ cod\ f2] \cdot_S ((f0 \otimes_S f1) \otimes_S f2)$ 
   $= (f0 \otimes_S f1 \otimes_S f2) \cdot_S a_S[dom\ f0,\ dom\ f1,\ dom\ f2]$ 
  using  $f0\ f1\ f2\ assocS-def\ tensor-assoc\ dom-tensor\ cod-tensor\ arr-tensor$ 
  comp-cod-arr [of f0 \otimes_S f1 \otimes_S f2 cod f0 \otimes_S cod f1 \otimes_S cod f2]
  comp-arr-dom [of f0 \otimes_S f1 \otimes_S f2 dom f0 \otimes_S dom f1 \otimes_S dom f2]
  by presburger
next
fix  $a\ b\ c\ d$ 
assume  $a$ : ide  $a$  and  $b$ : ide  $b$  and  $c$ : ide  $c$  and  $d$ : ide  $d$ 
show  $(a \otimes_S a_S[b,\ c,\ d]) \cdot_S a_S[a,\ b \otimes_S c,\ d] \cdot_S (a_S[a,\ b,\ c] \otimes_S d)$ 
   $= a_S[a,\ b,\ c \otimes_S d] \cdot_S a_S[a \otimes_S b,\ c,\ d]$ 
  unfolding assocS-def
  using  $a\ b\ c\ d\ tensor-assoc\ tensor-preserves-ide\ ideD\ tensor-in-hom$ 
  comp-arr-dom [of a \otimes_S b \otimes_S c \otimes_S d]
  by simp
qed

```

lemma *is-elementary-monoidal-category*:

shows *elementary-monoidal-category comp tensor_S \mathcal{I} (\lambda a. a) (\lambda a. a) assoc_S ..*

abbreviation T_{FSMC} **where** $T_{FSMC} \equiv EMC.T$
abbreviation α_{FSMC} **where** $\alpha_{FSMC} \equiv EMC.\alpha$
abbreviation ι_{FSMC} **where** $\iota_{FSMC} \equiv EMC.\iota$

lemma *is-monoidal-category*:
shows *monoidal-category comp* $T_{FSMC} \alpha_{FSMC} \iota_{FSMC}$
using *EMC.induces-monoidal-category by auto*

end

sublocale *free-strict-monoidal-category* \subseteq
elementary-monoidal-category comp tensor_S I λa. a λa. a assoc_S
using *is-elementary-monoidal-category by auto*

sublocale *free-strict-monoidal-category* \subseteq *monoidal-category comp* $T_{FSMC} \alpha_{FSMC} \iota_{FSMC}$
using *is-monoidal-category by auto*

sublocale *free-strict-monoidal-category* \subseteq
strict-monoidal-category comp $T_{FSMC} \alpha_{FSMC} \iota_{FSMC}$
using *tensor-preserves-ide lunit-agreement runit-agreement α-ide-simp assoc_S-def*
by *unfold-locales auto*

context *free-strict-monoidal-category*
begin

The inclusion of generators functor from C to $\mathcal{F}_S C$ is the composition of the inclusion of generators from C to $\mathcal{F}C$ and the diagonalization functor, which projects $\mathcal{F}C$ to $\mathcal{F}_S C$. As the diagonalization functor is the identity map on the image of C , the composite functor amounts to the corestriction to $\mathcal{F}_S C$ of the inclusion of generators of $\mathcal{F}C$.

interpretation D : *functor* $\mathcal{F}C.comp comp \mathcal{F}C.D$
using *FC.diagonalize-is-functor by auto*

interpretation I : *composite-functor* $C \mathcal{F}C.comp comp \mathcal{F}C.inclusion-of-generators \mathcal{F}C.D$
proof –

interpret *functor* $C \mathcal{F}C.comp \mathcal{F}C.inclusion-of-generators$
using *FC.inclusion-is-functor by blast*
show *composite-functor* $C \mathcal{F}C.comp comp \mathcal{F}C.inclusion-of-generators \mathcal{F}C.D ..$

qed

definition *inclusion-of-generators*
where *inclusion-of-generators* $\equiv \mathcal{F}C.inclusion-of-generators$

lemma *inclusion-is-functor*:
shows *functor* $C comp inclusion-of-generators$
using *FC.DoI-eq-I I.functor-axioms inclusion-of-generators-def*
by *auto*

The diagonalization functor is strict monoidal.

interpretation D : *strict-monoidal-functor* $\mathcal{F}C.comp \mathcal{F}C.T_{FMC} \mathcal{F}C.\alpha_{FMC} \mathcal{F}C.\iota_{FMC}$

comp $T_{FSMC} \alpha_{FSMC} \iota_{FSMC}$
 $FC.D$

proof

show $FC.D \text{ } FC.\iota = \iota$

proof –

have $FC.D \text{ } FC.\iota = FC.mkarr [FC.rep \text{ } FC.\iota]$

unfolding $FC.D-def$ **using** $FC.\iota-in-hom$ **by** *auto*

also have $\dots = FC.mkarr [1[[\mathcal{I}]]]$

using $FC.\iota-def$ $FC.rep-unity$ $FC.rep-lunit$ $FC.Par-Arr-norm$ $FC.Diagonalize-norm$

by *auto*

also have $\dots = \iota$

using $FC.unity_{FMC-def}$ $FC.\mathcal{I}-agreement$ $\iota-def$ **by** *simp*

finally show *?thesis* **by** *blast*

qed

show $\bigwedge f g. \llbracket FC.arr \text{ } f; FC.arr \text{ } g \rrbracket \implies$

$FC.D (FC.tensor \text{ } f \text{ } g) = tensor (FC.D \text{ } f) (FC.D \text{ } g)$

proof –

fix $f \text{ } g$

assume $f: FC.arr \text{ } f$ **and** $g: FC.arr \text{ } g$

have $fg: arr (FC.D \text{ } f) \wedge arr (FC.D \text{ } g)$

using $f \text{ } g \text{ } D.preserves-arr$ **by** *blast*

have $FC.D (FC.tensor \text{ } f \text{ } g) = f \otimes_S g$

using $tensor_S-def$ **by** *simp*

also have $f \otimes_S g = FC.D (f \otimes g)$

using $f \text{ } g \text{ } tensor_S-def$ **by** *simp*

also have $\dots = FC.D \text{ } f \otimes_S FC.D \text{ } g$

using $f \text{ } g \text{ } fg \text{ } tensor_S-def$ $FC.T-simp$ $FC.diagonalize-tensor$ $arr-char_{SbC}$

by (*metis* (*no-types*, *lifting*))

also have $\dots = tensor (FC.D \text{ } f) (FC.D \text{ } g)$

using $fg \text{ } T-simp$ **by** *simp*

finally show $FC.D (FC.tensor \text{ } f \text{ } g) = tensor (FC.D \text{ } f) (FC.D \text{ } g)$

by *blast*

qed

show $\bigwedge a \text{ } b \text{ } c. \llbracket FC.ide \text{ } a; FC.ide \text{ } b; FC.ide \text{ } c \rrbracket \implies$

$FC.D (FC.assoc \text{ } a \text{ } b \text{ } c) = assoc (FC.D \text{ } a) (FC.D \text{ } b) (FC.D \text{ } c)$

proof –

fix $a \text{ } b \text{ } c$

assume $a: FC.ide \text{ } a$ **and** $b: FC.ide \text{ } b$ **and** $c: FC.ide \text{ } c$

have $abc: ide (FC.D \text{ } a) \wedge ide (FC.D \text{ } b) \wedge ide (FC.D \text{ } c)$

using $a \text{ } b \text{ } c \text{ } D.preserves-ide$ **by** *blast*

have $abc': FC.ide (FC.D \text{ } a) \wedge FC.ide (FC.D \text{ } b) \wedge FC.ide (FC.D \text{ } c)$

using $a \text{ } b \text{ } c \text{ } D.preserves-ide$ $ide-char_{SbC}$ **by** *simp*

have $1: \bigwedge f g. FC.arr \text{ } f \implies FC.arr \text{ } g \implies f \otimes_S g = FC.D (f \otimes g)$

using $tensor_S-def$ **by** *simp*

have $2: \bigwedge f. ide \text{ } f \implies FC.ide \text{ } f$ **using** $ide-char_{SbC}$ **by** *blast*

have $assoc (FC.D \text{ } a) (FC.D \text{ } b) (FC.D \text{ } c) = FC.D \text{ } a \otimes_S FC.D \text{ } b \otimes_S FC.D \text{ } c$

using $abc \text{ } \alpha-ide-simp$ $assoc_S-def$ **by** *simp*

also have $\dots = FC.D \text{ } a \otimes_S FC.D (FC.D \text{ } b \otimes FC.D \text{ } c)$

using $abc' \text{ } 1$ **by** *auto*

also have $\dots = \mathcal{F}C.D \ a \otimes_S \mathcal{F}C.D \ (b \otimes c)$
using $b \ c \ \mathcal{F}C.diagonalize-tensor$ **by force**
also have $\dots = \mathcal{F}C.D \ (\mathcal{F}C.D \ a \otimes \mathcal{F}C.D \ (b \otimes c))$
using $1 \ b \ c \ abc \ D.preserves-ide \ \mathcal{F}C.tensor-preserves-ide \ ide-char_{SbC}$
by simp
also have $\dots = \mathcal{F}C.D \ (a \otimes b \otimes c)$
using $a \ b \ c \ \mathcal{F}C.diagonalize-tensor$ **by force**
also have $\dots = \mathcal{F}C.D \ a[a, b, c]$
proof –
have $\mathcal{F}C.can \ a[a, b, c]$ **using** $a \ b \ c \ \mathcal{F}C.can-assoc$ **by simp**
hence $\mathcal{F}C.ide \ (\mathcal{F}C.D \ a[a, b, c])$
using $a \ b \ c \ \mathcal{F}C.ide-diagonalize-can$ **by simp**
moreover have $\mathcal{F}C.cod \ (\mathcal{F}C.D \ a[a, b, c]) = \mathcal{F}C.D \ (a \otimes b \otimes c)$
using $a \ b \ c \ \mathcal{F}C.assoc-in-hom \ D.preserves-hom$
by $(metis \ (no-types, \ lifting) \ cod-char_{SbC} \ in-homE)$
ultimately show $?thesis$ **by simp**
qed
also have $\dots = \mathcal{F}C.D \ (\mathcal{F}C.assoc \ a \ b \ c)$
using $a \ b \ c$ **by simp**
finally show $\mathcal{F}C.D \ (\mathcal{F}C.assoc \ a \ b \ c) = assoc \ (\mathcal{F}C.D \ a) \ (\mathcal{F}C.D \ b) \ (\mathcal{F}C.D \ c)$
by blast
qed
qed

lemma *diagonalize-is-strict-monoidal-functor*:
shows *strict-monoidal-functor* $\mathcal{F}C.comp \ \mathcal{F}C.T_{FMC} \ \mathcal{F}C.\alpha_{FMC} \ \mathcal{F}C.\iota_{FMC}$
 $comp \ T_{FSMC} \ \alpha_{FSMC} \ \iota_{FSMC}$
 $\mathcal{F}C.D$

..

interpretation φ : *natural-isomorphism*
 $\mathcal{F}C.CC.comp \ comp \ D.T_D \ oFF.map \ D.FoT_C.map \ D.\varphi$
using $D.structure-naturalityisomorphism$ **by simp**

The diagonalization functor is part of a monoidal equivalence between the free monoidal category and the subcategory $\mathcal{F}_S C$.

interpretation E : *equivalence-of-categories* $comp \ \mathcal{F}C.comp \ \mathcal{F}C.D \ map \ \mathcal{F}C.\nu \ \mathcal{F}C.\mu$
using $\mathcal{F}C.is-equivalent-to-strict-subcategory$ **by auto**

interpretation D : *monoidal-functor* $\mathcal{F}C.comp \ \mathcal{F}C.T_{FMC} \ \mathcal{F}C.\alpha_{FMC} \ \mathcal{F}C.\iota_{FMC}$
 $comp \ T_{FSMC} \ \alpha_{FSMC} \ \iota_{FSMC}$
 $\mathcal{F}C.D \ D.\varphi$
using $D.monoidal-functor-axioms$ **by metis**

interpretation *equivalence-of-monoidal-categories* $comp \ T_{FSMC} \ \alpha_{FSMC} \ \iota_{FSMC}$
 $\mathcal{F}C.comp \ \mathcal{F}C.T_{FMC} \ \mathcal{F}C.\alpha_{FMC} \ \mathcal{F}C.\iota_{FMC}$
 $\mathcal{F}C.D \ D.\varphi \ \mathcal{I}$
 $map \ \mathcal{F}C.\nu \ \mathcal{F}C.\mu$

..

The category $\mathcal{F}C$ is monoidally equivalent to its subcategory $\mathcal{F}_S C$.

theorem *monoidally-equivalent-to-free-monoidal-category:*

shows *equivalence-of-monoidal-categories comp* $T_{FSMC} \alpha_{FSMC} \iota_{FSMC}$
 $\mathcal{F}C.comp \mathcal{F}C.T_{FMC} \mathcal{F}C.\alpha_{FMC} \mathcal{F}C.\iota_{FMC}$
 $\mathcal{F}C.D D.\varphi$
 $map \mathcal{F}C.\nu \mathcal{F}C.\mu$

..

end

We next show that the evaluation functor induced on the free monoidal category generated by C by a functor V from C to a strict monoidal category D restricts to a strict monoidal functor on the subcategory $\mathcal{F}_S C$.

locale *strict-evaluation-functor* =

D : *strict-monoidal-category* $D T_D \alpha_D \iota_D$ +
evaluation-map $C D T_D \alpha_D \iota_D V$ +
 $\mathcal{F}C$: *free-monoidal-category* C +
 E : *evaluation-functor* $C D T_D \alpha_D \iota_D V$ +
 $\mathcal{F}_S C$: *free-strict-monoidal-category* C
for $C :: 'c \text{ comp}$ (**infixr** $\langle \cdot_C \rangle$ 55)
and $D :: 'd \text{ comp}$ (**infixr** $\langle \cdot_D \rangle$ 55)
and $T_D :: 'd * 'd \Rightarrow 'd$
and $\alpha_D :: 'd * 'd * 'd \Rightarrow 'd$
and $\iota_D :: 'd$
and $V :: 'c \Rightarrow 'd$
begin

notation $\mathcal{F}C.in\text{-}hom$ ($\langle \langle - : - \rightarrow - \rangle \rangle$)

notation $\mathcal{F}_S C.in\text{-}hom$ ($\langle \langle - : - \rightarrow_S - \rangle \rangle$)

definition *map*

where $map \equiv \lambda f. \text{if } \mathcal{F}_S C.arr \ f \ \text{then } E.map \ f \ \text{else } D.null$

interpretation *functor* $\mathcal{F}_S C.comp \ D \ map$

unfolding *map-def*

apply *unfold-locales*

apply *simp*

using $\mathcal{F}_S C.arr\text{-}char_{SbC} \ E.preserves\text{-}arr$

apply *simp*

using $\mathcal{F}_S C.arr\text{-}char_{SbC} \ \mathcal{F}_S C.dom\text{-}char_{SbC} \ E.preserves\text{-}dom$

apply *simp*

using $\mathcal{F}_S C.arr\text{-}char_{SbC} \ \mathcal{F}_S C.cod\text{-}char_{SbC} \ E.preserves\text{-}cod$

apply *simp*

using $\mathcal{F}_S C.arr\text{-}char_{SbC} \ \mathcal{F}_S C.dom\text{-}char_{SbC} \ \mathcal{F}_S C.cod\text{-}char_{SbC} \ \mathcal{F}_S C.comp\text{-}char \ E.preserves\text{-}comp$

by (*elim* $\mathcal{F}_S C.seqE$, *auto*)

lemma *is-functor:*

shows functor $\mathcal{F}_S C.comp D map ..$

Every canonical arrow is an equivalence class of canonical terms. The evaluations in D of all such terms are identities, due to the strictness of D .

lemma *ide-eval-Can*:

shows $Can\ t \implies D.ide\ \{\!|t|\!\}$

proof (*induct t*)

show $\bigwedge x. Can\ \langle x \rangle \implies D.ide\ \{\!|\langle x \rangle|\!\}$ **by** *simp*

show $Can\ \mathcal{I} \implies D.ide\ \{\!|\mathcal{I}|\!\}$ **by** *simp*

show $\bigwedge t1\ t2. \llbracket Can\ t1 \implies D.ide\ \{\!|t1|\!\}; Can\ t2 \implies D.ide\ \{\!|t2|\!\}; Can\ (t1 \otimes t2) \rrbracket \implies D.ide\ \{\!|t1 \otimes t2|\!\}$

by *simp*

show $\bigwedge t1\ t2. \llbracket Can\ t1 \implies D.ide\ \{\!|t1|\!\}; Can\ t2 \implies D.ide\ \{\!|t2|\!\}; Can\ (t1 \cdot t2) \rrbracket \implies D.ide\ \{\!|t1 \cdot t2|\!\}$

proof –

fix $t1\ t2$

assume $t1: Can\ t1 \implies D.ide\ \{\!|t1|\!\}$

and $t2: Can\ t2 \implies D.ide\ \{\!|t2|\!\}$

and $t12: Can\ (t1 \cdot t2)$

show $D.ide\ \{\!|t1 \cdot t2|\!\}$

using $t1\ t2\ t12\ Can\text{-implies-Arr}\ eval\text{-in-hom}\ [of\ t1]\ eval\text{-in-hom}\ [of\ t2]\ D.comp\text{-ide-arr}$

by *fastforce*

qed

show $\bigwedge t. (Can\ t \implies D.ide\ \{\!|t|\!\}) \implies Can\ \mathbf{1}[t] \implies D.ide\ \{\!|\mathbf{1}[t]|\!\}$

using $D.strict\text{-lunit}$ **by** *simp*

show $\bigwedge t. (Can\ t \implies D.ide\ \{\!|t|\!\}) \implies Can\ \mathbf{1}^{-1}[t] \implies D.ide\ \{\!|\mathbf{1}^{-1}[t]|\!\}$

using $D.strict\text{-lunit}$ **by** *simp*

show $\bigwedge t. (Can\ t \implies D.ide\ \{\!|t|\!\}) \implies Can\ \mathbf{r}[t] \implies D.ide\ \{\!|\mathbf{r}[t]|\!\}$

using $D.strict\text{-runit}$ **by** *simp*

show $\bigwedge t. (Can\ t \implies D.ide\ \{\!|t|\!\}) \implies Can\ \mathbf{r}^{-1}[t] \implies D.ide\ \{\!|\mathbf{r}^{-1}[t]|\!\}$

using $D.strict\text{-runit}$ **by** *simp*

fix $t1\ t2\ t3$

assume $t1: Can\ t1 \implies D.ide\ \{\!|t1|\!\}$

and $t2: Can\ t2 \implies D.ide\ \{\!|t2|\!\}$

and $t3: Can\ t3 \implies D.ide\ \{\!|t3|\!\}$

show $Can\ \mathbf{a}[t1, t2, t3] \implies D.ide\ \{\!|\mathbf{a}[t1, t2, t3]|\!\}$

proof –

assume $Can\ \mathbf{a}[t1, t2, t3]$

hence $t123: D.ide\ \{\!|t1|\!\} \wedge D.ide\ \{\!|t2|\!\} \wedge D.ide\ \{\!|t3|\!\}$

using $t1\ t2\ t3$ **by** *simp*

have $\{\!|\mathbf{a}[t1, t2, t3]|\!\} = \{\!|t1|\!\} \otimes_D \{\!|t2|\!\} \otimes_D \{\!|t3|\!\}$

using $t123\ D.strict\text{-assoc}\ D.assoc\text{-in-hom}\ [of\ \{\!|t1|\!\}\ \{\!|t2|\!\}\ \{\!|t3|\!\}]$ **apply** *simp*

by (*elim D.in-homE, simp*)

thus *?thesis* **using** $t123$ **by** *simp*

qed

show $Can\ \mathbf{a}^{-1}[t1, t2, t3] \implies D.ide\ \{\!|\mathbf{a}^{-1}[t1, t2, t3]|\!\}$

proof –

assume $Can\ \mathbf{a}^{-1}[t1, t2, t3]$

hence $t123: Can\ t1 \wedge Can\ t2 \wedge Can\ t3 \wedge D.ide\ \{\!|t1|\!\} \wedge D.ide\ \{\!|t2|\!\} \wedge D.ide\ \{\!|t3|\!\}$

```

using  $t1\ t2\ t3$  by simp
have  $\{\mathbf{a}^{-1}[t1, t2, t3]\}$ 
  =  $D.inv\ a_D[D.cod\ \{t1\}, D.cod\ \{t2\}, D.cod\ \{t3\}] \cdot_D (\{t1\} \otimes_D \{t2\} \otimes_D \{t3\})$ 
  using  $t123\ eval\text{-}Assoc'$  [of  $t1\ t2\ t3$ ] Can-implies-Arr by simp
also have  $\dots = \{t1\} \otimes_D \{t2\} \otimes_D \{t3\}$ 
proof –
  have  $D.dom\ a_D[\{t1\}, \{t2\}, \{t3\}] = \{t1\} \otimes_D \{t2\} \otimes_D \{t3\}$ 
  proof –
    have  $D.dom\ a_D[\{t1\}, \{t2\}, \{t3\}] = D.cod\ a_D[\{t1\}, \{t2\}, \{t3\}]$ 
    using  $t123\ D.strict\text{-}assoc$  by simp
    also have  $\dots = \{t1\} \otimes_D \{t2\} \otimes_D \{t3\}$ 
    using  $t123$  by simp
    finally show ?thesis by blast
  qed
thus ?thesis
  using  $t123\ D.strict\text{-}assoc\ D.comp\text{-}arr\text{-}dom$  by auto
qed
finally have  $\{\mathbf{a}^{-1}[t1, t2, t3]\} = \{t1\} \otimes_D \{t2\} \otimes_D \{t3\}$  by blast
thus ?thesis using  $t123$  by auto
qed
qed

```

```

lemma ide-eval-can:
assumes  $\mathcal{F}C.can\ f$ 
shows  $D.ide\ (E.map\ f)$ 
proof –
  have  $f = \mathcal{F}C.mkarr\ (\mathcal{F}C.rep\ f)$ 
  using assms  $\mathcal{F}C.can\text{-}implies\text{-}arr\ \mathcal{F}C.mkarr\text{-}rep$  by blast
moreover have  $1: Can\ (\mathcal{F}C.rep\ f)$ 
  using assms  $\mathcal{F}C.Can\text{-}rep\text{-}can$  by simp
moreover have  $D.ide\ \{\mathcal{F}C.rep\ f\}$ 
  using assms ide-eval-Can by (simp add: 1)
ultimately show ?thesis using assms  $\mathcal{F}C.can\text{-}implies\text{-}arr\ E.map\text{-}def$  by force
qed

```

Diagonalization transports formal arrows naturally along reductions, which are canonical terms and therefore evaluate to identities of D . It follows that the evaluation in D of a formal arrow is equal to the evaluation of its diagonalization.

```

lemma map-diagonalize:
assumes  $f: \mathcal{F}C.arr\ f$ 
shows  $E.map\ (\mathcal{F}C.D\ f) = E.map\ f$ 
proof –
  interpret  $EQ: equivalence\text{-}of\text{-}categories$ 
     $\mathcal{F}_S C.comp\ \mathcal{F}C.comp\ \mathcal{F}C.D\ \mathcal{F}_S C.map\ \mathcal{F}C.\nu\ \mathcal{F}C.\mu$ 
  using  $\mathcal{F}C.is\text{-}equivalent\text{-}to\text{-}strict\text{-}subcategory$  by auto
have  $1: \mathcal{F}C.seq\ (\mathcal{F}_S C.map\ (\mathcal{F}C.D\ f))\ (\mathcal{F}C.\nu\ (\mathcal{F}C.dom\ f))$ 
proof
  show  $\langle\langle \mathcal{F}C.\nu\ (\mathcal{F}C.dom\ f) : \mathcal{F}C.dom\ f \rightarrow \mathcal{F}C.D\ (\mathcal{F}C.dom\ f) \rangle\rangle$ 
  using  $f\ \mathcal{F}_S C.map\text{-}simp\ EQ.F.preserves\text{-}arr$ 

```

by (*intro FC.in-homI, simp-all*)
show « $\mathcal{F}_S C.map (FC.D f) : FC.D (FC.dom f) \rightarrow FC.cod (FC.D f)$ »
 by (*metis (no-types, lifting) EQ.F.preserves-dom EQ.F.preserves-reflects-arr*
 $\mathcal{F}_S C.arr\text{-}iff\text{-}in\text{-}hom \mathcal{F}_S C.cod\text{-}simp \mathcal{F}_S C.in\text{-}hom\text{-}char_{SbC} \mathcal{F}_S C.map\text{-}simp f$)
qed
have $E.map (FC.v (FC.cod f)) \cdot_D E.map f =$
 $E.map (FC.D f) \cdot_D E.map (FC.v (FC.dom f))$
proof –
have $E.map (FC.v (FC.cod f)) \cdot_D E.map f = E.map (FC.v (FC.cod f) \cdot f)$
 using f by *simp*
also have $\dots = E.map (FC.D f \cdot FC.v (FC.dom f))$
 using f *EQ.eta.naturality* $\mathcal{F}_S C.map\text{-}simp$ *EQ.F.preserves-arr* by *simp*
also have $\dots = E.map (\mathcal{F}_S C.map (FC.D f)) \cdot_D E.map (FC.v (FC.dom f))$
 using f *1* *E.as-nat-trans.preserves-comp-2* *EQ.F.preserves-arr* $\mathcal{F}_S C.map\text{-}simp$
 by (*metis (no-types, lifting)*)
also have $\dots = E.map (FC.D f) \cdot_D E.map (FC.v (FC.dom f))$
 using f *EQ.F.preserves-arr* $\mathcal{F}_S C.map\text{-}simp$ by *simp*
finally show *?thesis* by *blast*
qed
moreover have $\bigwedge a. FC.ide a \implies D.ide (E.map (FC.v a))$
 using $FC.v\text{-}def$ $FC.Arr\text{-}rep$ *Arr-implies-Ide-Cod* *Can-red* $FC.can\text{-}mkarr\text{-}Can$
ide-eval-can
 by (*metis (no-types, lifting) EQ.eta.preserves-reflects-arr FC.seqE*
 $FC.comp\text{-}preserves\text{-}can$ $FC.ideD(1)$ $FC.ide\text{-}implies\text{-}can$)
moreover have $D.cod (E.map f) = D.dom (E.map (FC.v (FC.cod f)))$
 using f *E.preserves-hom* *EQ.eta.preserves-hom* by *simp*
moreover have $D.dom (E.map (FC.D f)) = D.cod (E.map (FC.v (FC.dom f)))$
 using f *1* *E.preserves-seq* *EQ.F.preserves-arr* $\mathcal{F}_S C.map\text{-}simp$ by *auto*
ultimately show *?thesis*
 using f *D.comp-arr-dom* *D.ideD* *D.arr-dom-iff-arr* *E.as-nat-trans.naturality2*
 by (*metis E.preserves-cod FC.ide-cod FC.ide-dom*)
qed

lemma *strictly-preserves-tensor*:
assumes $\mathcal{F}_S C.arr f$ **and** $\mathcal{F}_S C.arr g$
shows $map (\mathcal{F}_S C.tensor f g) = map f \otimes_D map g$
proof –
have $1: \mathcal{F}_S C.arr (f \otimes g)$
 using *assms* $\mathcal{F}_S C.arr\text{-}char_{SbC}$ $FC.tensor\text{-}in\text{-}hom$ by *auto*
have $2: \mathcal{F}_S C.arr (\mathcal{F}_S C.tensor f g)$
 using *assms* $\mathcal{F}_S C.tensor\text{-}in\text{-}hom$ [*of f g*] $\mathcal{F}_S C.T\text{-}simp$ by *fastforce*
have $map (\mathcal{F}_S C.tensor f g) = E.map (f \otimes g)$
proof –
have $map (\mathcal{F}_S C.tensor f g) = map (f \otimes_S g)$
 using *assms* $\mathcal{F}_S C.T\text{-}simp$ by *simp*
also have $\dots = map (FC.D (f \otimes g))$
 using *assms* $FC.tensor_{FMC}\text{-}def$ $\mathcal{F}_S C.tensor_S\text{-}def$ $\mathcal{F}_S C.arr\text{-}char_{SbC}$ by *force*
also have $\dots = E.map (f \otimes g)$
proof –

```

interpret Diag: functor  $\mathcal{F}C.comp \mathcal{F}_S C.comp \mathcal{F}C.D$ 
  using  $\mathcal{F}C.diagonalize-is-functor$  by auto
show ?thesis
  using  $assms\ 1\ map-diagonalize\ [of\ f\ \otimes\ g]\ Diag.preserves-arr\ map-def$  by simp
qed
finally show ?thesis by blast
qed
thus ?thesis
  using  $assms\ \mathcal{F}_S C.arr-char_{SbC}\ E.strictly-preserves-tensor\ map-def$  by simp
qed

lemma is-strict-monoidal-functor:
shows strict-monoidal-functor  $\mathcal{F}_S C.comp \mathcal{F}_S C.T_{FSMC} \mathcal{F}_S C.\alpha \mathcal{F}_S C.\iota D T_D \alpha_D \iota_D map$ 
proof
show  $\bigwedge f\ g.\ \mathcal{F}_S C.arr\ f \implies \mathcal{F}_S C.arr\ g \implies map\ (\mathcal{F}_S C.tensor\ f\ g) = map\ f \otimes_D map\ g$ 
  using  $strictly-preserves-tensor$  by fast
show  $map\ \mathcal{F}_S C.\iota = \iota_D$ 
using  $\mathcal{F}_S C.arr-unity\ \mathcal{F}_S C.\iota-def\ map-def\ E.map-def\ \mathcal{F}C.rep-mkarr\ E.eval-norm\ D.strict-unit$ 
  by auto
fix a b c
assume a:  $\mathcal{F}_S C.ide\ a$  and b:  $\mathcal{F}_S C.ide\ b$  and c:  $\mathcal{F}_S C.ide\ c$ 
show  $map\ (\mathcal{F}_S C.assoc\ a\ b\ c) = a_D[map\ a,\ map\ b,\ map\ c]$ 
proof -
have  $map\ (\mathcal{F}_S C.assoc\ a\ b\ c) = map\ a \otimes_D map\ b \otimes_D map\ c$ 
  using a b c  $\mathcal{F}_S C.\alpha-def\ \mathcal{F}_S C.assoc_S-def\ \mathcal{F}_S C.arr-tensor\ \mathcal{F}_S C.T-simp\ \mathcal{F}_S C.ideD(1)$ 
  strictly-preserves-tensor  $\mathcal{F}_S C.\alpha-ide-simp$ 
  by presburger
also have ... =  $a_D[map\ a,\ map\ b,\ map\ c]$ 
  using a b c  $D.strict-assoc\ D.assoc-in-hom\ [of\ map\ a\ map\ b\ map\ c]$  by auto
finally show ?thesis by blast
qed
qed

end

sublocale strict-evaluation-functor  $\subseteq$ 
  strict-monoidal-functor  $\mathcal{F}_S C.comp \mathcal{F}_S C.T_{FSMC} \mathcal{F}_S C.\alpha \mathcal{F}_S C.\iota D T_D \alpha_D \iota_D map$ 
  using is-strict-monoidal-functor by auto

locale strict-monoidal-extension-to-free-strict-monoidal-category =
  C: category C +
  monoidal-language C +
   $\mathcal{F}_S C$ : free-strict-monoidal-category C +
  strict-monoidal-extension C  $\mathcal{F}_S C.comp \mathcal{F}_S C.T_{FSMC} \mathcal{F}_S C.\alpha \mathcal{F}_S C.\iota D T_D \alpha_D \iota_D$ 
   $\mathcal{F}_S C.inclusion-of-generators\ V\ F$ 
for C :: 'c comp (infixr '<_C>' 55)
and D :: 'd comp (infixr '<_D>' 55)
and  $T_D :: 'd * 'd \Rightarrow 'd$ 
and  $\alpha_D :: 'd * 'd * 'd \Rightarrow 'd$ 

```

```

and  $\iota_D :: 'd$ 
and  $V :: 'c \Rightarrow 'd$ 
and  $F :: 'c \text{ free-monoidal-category.arr} \Rightarrow 'd$ 

sublocale strict-evaluation-functor  $\subseteq$ 
    strict-monoidal-extension  $C \mathcal{F}_S C.comp \mathcal{F}_S C.T_{FSMC} \mathcal{F}_S C.\alpha \mathcal{F}_S C.\iota D T_D \alpha_D \iota_D$ 
     $\mathcal{F}_S C.inclusion-of-generators$   $V \text{ map}$ 

proof –
  interpret  $V$ : functor  $C \mathcal{F}_S C.comp \mathcal{F}_S C.inclusion-of-generators$ 
    using  $\mathcal{F}_S C.inclusion-is-functor$  by auto
  show strict-monoidal-extension  $C \mathcal{F}_S C.comp \mathcal{F}_S C.T_{FSMC} \mathcal{F}_S C.\alpha \mathcal{F}_S C.\iota D T_D \alpha_D \iota_D$ 
     $\mathcal{F}_S C.inclusion-of-generators$   $V \text{ map}$ 

  proof
    show  $\forall f. C.arr f \longrightarrow \text{map} (\mathcal{F}_S C.inclusion-of-generators f) = V f$ 
      using  $V.preserves-arr E.is-extension \text{map-def } \mathcal{F}_S C.inclusion-of-generators-def$  by simp
    qed
  qed

context free-strict-monoidal-category
begin

```

We now have the main result of this section: the evaluation functor on $\mathcal{F}_S C$ induced by a functor V from C to a strict monoidal category D is the unique strict monoidal extension of V to $\mathcal{F}_S C$.

```

theorem is-free:
assumes strict-monoidal-category  $D T_D \alpha_D \iota_D$ 
and strict-monoidal-extension-to-free-strict-monoidal-category  $C D T_D \alpha_D \iota_D V F$ 
shows  $F = \text{strict-evaluation-functor.map } C D T_D \alpha_D \iota_D V$ 
proof –
  interpret  $D$ : strict-monoidal-category  $D T_D \alpha_D \iota_D$ 
    using assms(1) by auto

```

Let F be a given extension of V to a strict monoidal functor defined on $\mathcal{F}_S C$.

```

interpret  $F$ : strict-monoidal-extension-to-free-strict-monoidal-category
     $C D T_D \alpha_D \iota_D V F$ 
using assms(2) by auto

```

Let E_S be the evaluation functor from $\mathcal{F}_S C$ to D induced by V . Then E_S is also a strict monoidal extension of V .

```

interpret  $E_S$ : strict-evaluation-functor  $C D T_D \alpha_D \iota_D V ..$ 

```

Let D be the strict monoidal functor $\mathcal{F}C.D$ that projects $\mathcal{F}C$ to the subcategory $\mathcal{F}_S C$.

```

interpret  $D$ : functor  $\mathcal{F}C.comp \text{comp } \mathcal{F}C.D$ 
  using  $\mathcal{F}C.diagonalize-is-functor$  by auto
interpret  $D$ : strict-monoidal-functor  $\mathcal{F}C.comp \mathcal{F}C.T_{FMC} \mathcal{F}C.\alpha \mathcal{F}C.\iota$ 
     $\text{comp } T_{FSMC} \alpha \iota$ 
     $\mathcal{F}C.D$ 
using diagonalize-is-strict-monoidal-functor by blast

```

The composite functor $F \circ D$ is also an extension of V to a strict monoidal functor on $\mathcal{F}C$.

```

interpret FoD: composite-functor  $\mathcal{F}C.comp \text{ comp } D \mathcal{F}C.D F ..$ 
interpret FoD: strict-monoidal-functor
            $\mathcal{F}C.comp \mathcal{F}C.T_{FMC} \mathcal{F}C.\alpha \mathcal{F}C.\iota D T_D \alpha_D \iota_D \langle F \circ \mathcal{F}C.D \rangle$ 
using  $D.strict\text{-monoidal-functor-axioms } F.strict\text{-monoidal-functor-axioms}$ 
        $strict\text{-monoidal-functors-compose}$ 
by fast
interpret FoD: strict-monoidal-extension-to-free-monoidal-category
            $C D T_D \alpha_D \iota_D V FoD.map$ 
proof
show  $\forall f. C.arr f \longrightarrow FoD.map (FC.inclusion\text{-of-generators } f) = V f$ 
proof –
  have  $\bigwedge f. C.arr f \implies FoD.map (FC.inclusion\text{-of-generators } f) = V f$ 
proof –
  fix  $f$ 
  assume  $f: C.arr f$ 
  have  $FoD.map (FC.inclusion\text{-of-generators } f)$ 
        $= F (\mathcal{F}C.D (FC.inclusion\text{-of-generators } f))$ 
  using  $f$  by simp
  also have  $... = F (inclusion\text{-of-generators } f)$ 
  using  $f$   $\mathcal{F}C.strict\text{-arr-char}' F.I.preserves\text{-arr } inclusion\text{-of-generators-def}$  by simp
  also have  $... = V f$ 
  using  $f$   $F.is\text{-extension}$  by simp
  finally show  $FoD.map (FC.inclusion\text{-of-generators } f) = V f$ 
  by blast
qed
thus ?thesis by blast
qed
qed

```

By the freeness of $\mathcal{F}C$, we have that $F \circ D$ is equal to the evaluation functor $E_S.E.map$ induced by V on $\mathcal{F}C$. Moreover, $E_S.map$ coincides with $E_S.E.map$ on $\mathcal{F}_S C$ and $F \circ D$ coincides with F on $\mathcal{F}_S C$. Therefore, F coincides with E on their common domain $\mathcal{F}_S C$, showing $F = E_S.map$.

```

have  $\bigwedge f. arr f \implies F f = E_S.map f$ 
using  $\mathcal{F}C.strict\text{-arr-char}' \mathcal{F}C.is\text{-free [of } D] E_S.E.evaluation\text{-functor-axioms}$ 
        $FoD.strict\text{-monoidal-extension-to-free-monoidal-category-axioms } E_S.map\text{-def}$ 
by simp
moreover have  $\bigwedge f. \neg arr f \implies F f = E_S.map f$ 
using  $F.extensionality E_S.extensionality arr\text{-char}_{SbC}$  by auto
ultimately show  $F = E_S.map$  by blast
qed

```

end

end

Chapter 5

Cartesian Monoidal Category

```
theory CartesianMonoidalCategory
imports MonoidalCategory Category3.CartesianCategory
begin
```

5.1 Symmetric Monoidal Category

```
locale symmetric-monoidal-category =
  monoidal-category C T  $\alpha$   $\iota$  +
  S: symmetry-functor C C +
  ToS: composite-functor CC.comp CC.comp C S.map T +
   $\sigma$ : natural-isomorphism CC.comp C T ToS.map  $\sigma$ 
for C :: 'a comp (infixr <·> 55)
and T :: 'a * 'a  $\Rightarrow$  'a
and  $\alpha$  :: 'a * 'a * 'a  $\Rightarrow$  'a
and  $\iota$  :: 'a
and  $\sigma$  :: 'a * 'a  $\Rightarrow$  'a +
assumes sym-inverse:  $\llbracket$  ide a; ide b  $\rrbracket \Longrightarrow$  inverse-arrows ( $\sigma$  (a, b)) ( $\sigma$  (b, a))
and unitor-coherence: ide a  $\Longrightarrow$  l[a] ·  $\sigma$  (a, I) = r[a]
and assoc-coherence:  $\llbracket$  ide a; ide b; ide c  $\rrbracket \Longrightarrow$ 
   $\alpha$  (b, c, a) ·  $\sigma$  (a, b  $\otimes$  c) ·  $\alpha$  (a, b, c)
  = (b  $\otimes$   $\sigma$  (a, c)) ·  $\alpha$  (b, a, c) · ( $\sigma$  (a, b)  $\otimes$  c)
begin

  abbreviation sym (s[-, -])
  where sym a b  $\equiv$   $\sigma$  (a, b)

end
```

```
locale elementary-symmetric-monoidal-category =
  elementary-monoidal-category C tensor unity lunit runit assoc
for C :: 'a comp (infixr <·> 55)
and tensor :: 'a  $\Rightarrow$  'a  $\Rightarrow$  'a (infixr < $\otimes$ > 53)
and unity :: 'a (⟨I⟩)
and lunit :: 'a  $\Rightarrow$  'a (⟨l[-]⟩)
```

```

and runit :: 'a ⇒ 'a                (⟦r[-]⟧)
and assoc :: 'a ⇒ 'a ⇒ 'a ⇒ 'a    (⟦a[-, -, -]⟧)
and sym :: 'a ⇒ 'a ⇒ 'a            (⟦s[-, -]⟧) +
assumes sym-in-hom: [⟦ide a; ide b⟧] ⇒ «s[a, b] : a ⊗ b → b ⊗ a»
and sym-naturality: [⟦arr f; arr g⟧] ⇒ s[cod f, cod g] · (f ⊗ g) = (g ⊗ f) · s[dom f, dom g]
and sym-inverse: [⟦ide a; ide b⟧] ⇒ inverse-arrows s[a, b] s[b, a]
and unit-coherence: ide a ⇒ l[a] · s[a, I] = r[a]
and assoc-coherence: [⟦ide a; ide b; ide c⟧] ⇒
    a[b, c, a] · s[a, b ⊗ c] · a[a, b, c]
    = (b ⊗ s[a, c]) · a[b, a, c] · (s[a, b] ⊗ c)

```

begin

```

lemma sym-simps [simp]:
assumes ide a and ide b
shows arr s[a, b]
and dom s[a, b] = a ⊗ b
and cod s[a, b] = b ⊗ a
using assms sym-in-hom by auto

```

```

interpretation CC: product-category C C ..
sublocale MC: monoidal-category C T α ι
using induces-monoidal-category by simp

```

```

interpretation S: symmetry-functor C C ..
interpretation ToS: composite-functor CC.comp CC.comp C S.map T ..

```

```

definition σ :: 'a * 'a ⇒ 'a
where σ f ≡ if CC.arr f then s[cod (fst f), cod (snd f)] · (fst f ⊗ snd f) else null

```

```

interpretation σ: natural-isomorphism CC.comp C T ToS.map σ

```

proof –

```

interpret σ: transformation-by-components CC.comp C T ToS.map λa. s[fst a, snd a]
using sym-in-hom sym-naturality
by unfold-locales auto
interpret σ: natural-isomorphism CC.comp C T ToS.map σ.map
using sym-inverse σ.map-simp-ide
by unfold-locales auto
have σ = σ.map
using σ-def σ.map-def sym-naturality by fastforce
thus natural-isomorphism CC.comp C T ToS.map σ
using σ.natural-isomorphism-axioms by presburger

```

qed

```

interpretation symmetric-monoidal-category C T α ι σ

```

proof

```

show  $\bigwedge a b. [⟦ide a; ide b⟧] ⇒ \textit{inverse-arrows} (\sigma (a, b)) (\sigma (b, a))$ 
using sym-inverse comp-arr-dom σ-def by auto
show  $\bigwedge a. \textit{ide a} ⇒ \textit{MC.lunit a} \cdot \sigma (a, \textit{MC.unity}) = \textit{MC.runit a}$ 
using lunit-agreement I-agreement sym-in-hom comp-arr-dom

```



```

    unitor-coherence runit-agreement  $\sigma$ -def
  by simp
  show  $\bigwedge a b c. \llbracket \text{ide } a; \text{ide } b; \text{ide } c \rrbracket \implies$ 
     $MC.assoc\ b\ c\ a \cdot \sigma\ (a, MC.tensor\ b\ c) \cdot MC.assoc\ a\ b\ c =$ 
     $MC.tensor\ b\ (\sigma\ (a, c)) \cdot MC.assoc\ b\ a\ c \cdot MC.tensor\ (\sigma\ (a, b))\ c$ 
  using sym-in-hom tensor-preserves-ide  $\sigma$ -def assoc-coherence
    comp-arr-dom comp-cod-arr
  by simp
qed

lemma induces-symmetric-monoidal-categoryCMC:
shows symmetric-monoidal-category  $C\ T\ \alpha\ \iota\ \sigma$ 
..

end

context symmetric-monoidal-category
begin

interpretation EMC: elementary-monoidal-category  $C$  tensor unity lunit runit assoc
  using induces-elementary-monoidal-category by auto

lemma induces-elementary-symmetric-monoidal-categoryCMC:
shows elementary-symmetric-monoidal-category
   $C$  tensor unity lunit runit assoc  $(\lambda a b. \sigma\ (a, b))$ 
  using  $\sigma$ .naturality unitor-coherence assoc-coherence sym-inverse
  by unfold-locales auto

end

locale dual-symmetric-monoidal-category =
   $M$ : symmetric-monoidal-category
begin

sublocale dual-monoidal-category  $C\ T\ \alpha\ \iota\ ..$ 
interpretation  $S$ : symmetry-functor comp comp ..
interpretation ToS: composite-functor  $MM.comp\ MM.comp\ comp\ S.map\ T\ ..$ 
sublocale  $\sigma'$ : inverse-transformation  $M.CC.comp\ C\ T\ M.ToS.map\ \sigma\ ..$ 
interpretation  $\sigma$ : natural-transformation  $MM.comp\ comp\ T\ ToS.map\ \sigma'.map$ 
  using  $\sigma'.extensionality\ \sigma'.naturality1\ \sigma'.naturality2$ 
  by unfold-locales auto
interpretation  $\sigma$ : natural-isomorphism  $MM.comp\ comp\ T\ ToS.map\ \sigma'.map$ 
  by unfold-locales auto

sublocale symmetric-monoidal-category comp  $T\ M.\alpha'\ \langle M.inv\ \iota \rangle\ \sigma'.map$ 
proof
show  $\bigwedge a b. \llbracket \text{ide } a; \text{ide } b \rrbracket \implies \text{inverse-arrows}\ (\sigma'.map\ (a, b))\ (\sigma'.map\ (b, a))$ 
  apply auto
  by (metis  $M.inverse-arrowsE\ M.inverse-unique\ M.isoI\ M.sym-inverse\ ide-char$ )

```

```

      iso-char comp-def section-retraction-of-iso(1))
show  $\bigwedge a. \text{ide } a \implies \text{lunit } a \cdot^{op} \sigma'.\text{map } (a, \text{unity}) = \text{runit } a$ 
  using M.unitor-coherence M.unit-in-hom M.unit-is-iso lunit-char runit-char
  apply auto
  by (metis M.inv-comp-left(1) M.iso-lunit M.iso-runit)
show  $\bigwedge a b c.$ 
   $[\text{ide } a; \text{ide } b; \text{ide } c]$ 
   $\implies \text{assoc } b c a \cdot^{op} \sigma'.\text{map } (a, \text{tensor } b c) \cdot^{op} \text{assoc } a b c =$ 
     $(\text{tensor } b (\sigma'.\text{map } (a, c))) \cdot^{op} \text{assoc } b a c \cdot^{op} (\text{tensor } (\sigma'.\text{map } (a, b)) c)$ 
proof -
  fix a b c
  assume a: ide a and b: ide b and c: ide c
  show  $\text{assoc } b c a \cdot^{op} \sigma'.\text{map } (a, \text{tensor } b c) \cdot^{op} \text{assoc } a b c =$ 
     $(\text{tensor } b (\sigma'.\text{map } (a, c))) \cdot^{op} \text{assoc } b a c \cdot^{op} (\text{tensor } (\sigma'.\text{map } (a, b)) c)$ 
  proof -
    have  $\text{assoc } b c a \cdot^{op} \sigma'.\text{map } (a, \text{tensor } b c) \cdot^{op} \text{assoc } a b c =$ 
       $(a^{-1}[a, b, c] \cdot M.\text{inv } s[a, \text{tensor } b c]) \cdot a^{-1}[b, c, a]$ 
    using a b c by auto
    also have ... =  $M.\text{inv } (s[a, \text{tensor } b c] \cdot M.\text{assoc } a b c) \cdot M.\text{inv } (M.\text{assoc } b c a)$ 
    using a b c M.iso-assoc M.inv-comp by auto
    also have ... =  $M.\text{inv } (M.\text{assoc } b c a \cdot s[a, \text{tensor } b c] \cdot M.\text{assoc } a b c)$ 
    using a b c M.iso-assoc
       $M.\text{inv-comp } [of s[a, \text{tensor } b c] \cdot M.\text{assoc } a b c M.\text{assoc } b c a]$ 
    by fastforce
    also have ... =  $M.\text{inv } (\text{tensor } b s[a, c] \cdot a[b, a, c] \cdot (\text{tensor } s[a, b] c))$ 
    using a b c M.assoc-coherence by simp
    also have ... =  $M.\text{inv } (a[b, a, c] \cdot (\text{tensor } s[a, b] c)) \cdot M.\text{inv } (\text{tensor } b s[a, c])$ 
    using a b c M.iso-assoc
       $M.\text{inv-comp } [of a[b, a, c] \cdot (\text{tensor } s[a, b] c)]$ 
    by fastforce
    also have ... =
       $(\text{tensor } (M.\text{inv } s[a, b]) c \cdot M.\text{inv } a[b, a, c]) \cdot \text{tensor } b (M.\text{inv } s[a, c])$ 
    using a b c M.iso-assoc M.inv-comp by simp
    also have ... =
       $(\text{tensor } b (\sigma'.\text{map } (a, c))) \cdot^{op} \text{assoc } b a c \cdot^{op} (\text{tensor } (\sigma'.\text{map } (a, b)) c)$ 
    using a b c by auto
    finally show ?thesis by simp
  qed
qed
qed

```

lemma *is-symmetric-monoidal-category:*

shows *symmetric-monoidal-category comp T M. α' (M.inv ι) σ' .map*

..

end

5.2 Cartesian Monoidal Category

Here we define “cartesian monoidal category” by imposing additional properties, but not additional structure, on top of “monoidal category”. The additional properties are that the unit is a terminal object and that the tensor is a categorical product, with projections defined in terms of unitors, terminators, and tensor. It then follows that the associators are induced by the product structure.

```

locale cartesian-monoidal-category =
  monoidal-category C T  $\alpha$   $\iota$ 
for C :: 'a comp (infixr <·> 55)
and T :: 'a * 'a  $\Rightarrow$  'a
and  $\alpha$  :: 'a * 'a * 'a  $\Rightarrow$  'a
and  $\iota$  :: 'a +
assumes terminal-unity: terminal  $\mathcal{I}$ 
and tensor-is-product:
  [[ide a; ide b;  $\langle t_a : a \rightarrow \mathcal{I} \rangle$ ;  $\langle t_b : b \rightarrow \mathcal{I} \rangle$ ]]  $\Longrightarrow$ 
  has-as-binary-product a b (r[a] · (a  $\otimes$  t_b)) (l[b] · (t_a  $\otimes$  b))
begin

  sublocale category-with-terminal-object
    using terminal-unity by unfold-locales blast

  lemma is-category-with-terminal-object:
  shows category-with-terminal-object C
  ..

  definition the-trm ( $\langle t[-] \rangle$ )
  where the-trm  $\equiv \lambda f. \text{THE } t. \langle t : \text{dom } f \rightarrow \mathcal{I} \rangle$ 

  lemma trm-in-hom [intro]:
  assumes ide a
  shows  $\langle t[a] : a \rightarrow \mathcal{I} \rangle$ 
  unfolding the-trm-def
  using assms theI [of  $\lambda t. \langle t : \text{dom } a \rightarrow \mathcal{I} \rangle$ ] terminal-unity terminal-arr-unique
  by (metis ideD(2) terminalE)

  lemma trm-simps [simp]:
  assumes ide a
  shows arr t[a] and dom t[a] = a and cod t[a] =  $\mathcal{I}$ 
  using assms trm-in-hom by auto

  interpretation elementary-category-with-terminal-object C  $\mathcal{I}$  the-trm
  proof
  show ide  $\mathcal{I}$ 
  using ide-unity by blast
  fix a
  show ide a  $\Longrightarrow \langle \text{the-trm } a : a \rightarrow \mathcal{I} \rangle$ 
  using the-trm-def theI [of  $\lambda t. \langle t : \text{dom } a \rightarrow \mathcal{I} \rangle$ ] terminalE terminal-unity by auto

```

thus $\wedge f. \llbracket \text{ide } a; \langle f : a \rightarrow \mathcal{I} \rangle \rrbracket \implies f = \text{the-trm } a$
using *theI* [*of* $\lambda t. \langle t : \text{dom } a \rightarrow \mathcal{I} \rangle$]
by (*metis terminalE terminal-unity*)
qed

lemma *extends-to-elementary-category-with-terminal-object*_{CMC}:
shows *elementary-category-with-terminal-object* $C \mathcal{I}$ *the-trm*
 ..

definition *pr₀* ($\langle \mathfrak{p}_0[-, -] \rangle$)
where *pr₀* $a \ b \equiv l[b] \cdot (t[a] \otimes b)$

definition *pr₁* ($\langle \mathfrak{p}_1[-, -] \rangle$)
where *pr₁* $a \ b \equiv r[a] \cdot (a \otimes t[b])$

sublocale *ECC: elementary-category-with-binary-products* $C \text{ pr}_0 \text{ pr}_1$
proof

fix $f \ g$
assume fg : *span* $f \ g$
have *has-as-binary-product* (*cod* f) (*cod* g) $\mathfrak{p}_1[\text{cod } f, \text{cod } g] \ \mathfrak{p}_0[\text{cod } f, \text{cod } g]$
using fg *tensor-is-product pr₀-def pr₁-def* **by** *auto*
thus $\exists ! l. \mathfrak{p}_1[\text{cod } f, \text{cod } g] \cdot l = f \wedge \mathfrak{p}_0[\text{cod } f, \text{cod } g] \cdot l = g$
using fg
by (*elim has-as-binary-productE*) *blast*
qed (*unfold pr₀-def pr₁-def, auto*)

lemma *induces-elementary-category-with-binary-products*_{CMC}:
shows *elementary-category-with-binary-products* $C \text{ pr}_0 \text{ pr}_1$
 ..

lemma *is-category-with-binary-products*:
shows *category-with-binary-products* C
using *ECC.is-category-with-binary-products* **by** *blast*

sublocale *category-with-binary-products* C
using *is-category-with-binary-products* **by** *blast*

sublocale *ECC: elementary-cartesian-category* $C \text{ pr}_0 \text{ pr}_1 \mathcal{I}$ *the-trm* ..

lemma *extends-to-elementary-cartesian-category*_{CMC}:
shows *elementary-cartesian-category* $C \text{ pr}_0 \text{ pr}_1 \mathcal{I}$ *the-trm*
 ..

lemma *is-cartesian-category*:
shows *cartesian-category* C
using *ECC.is-cartesian-category* **by** *simp*

sublocale *cartesian-category C*
using *is-cartesian-category* **by** *blast*

abbreviation *dup* ($\langle d[-] \rangle$)
where *dup* \equiv *ECC.dup*

abbreviation *tuple* ($\langle \langle -, - \rangle \rangle$)
where $\langle f, g \rangle \equiv$ *ECC.tuple f g*

lemma *prod-eq-tensor*:
shows *ECC.prod = tensor*
proof –

have $\bigwedge f g. \text{ECC.prod } f g = f \otimes g$

proof –

fix *f g*

show *ECC.prod f g = f \otimes g*

proof (*cases arr f \wedge arr g*)

show $\neg (\text{arr } f \wedge \text{arr } g) \implies ?thesis$

by (*metis CC.arrE ECC.prod-def ECC.tuple-ext T.extensionality fst-conv seqE snd-conv*)

assume *0: arr f \wedge arr g*

have *1: span (f \cdot p₁[dom f, dom g]) (g \cdot p₀[dom f, dom g])*

using *0* **by** *simp*

have $\text{p}_1[\text{cod } f, \text{cod } g] \cdot \text{ECC.prod } f g = \text{p}_1[\text{cod } f, \text{cod } g] \cdot (f \otimes g)$

proof –

have $\text{p}_1[\text{cod } f, \text{cod } g] \cdot \text{ECC.prod } f g =$

$\text{p}_1[\text{cod } f, \text{cod } g] \cdot \langle f \cdot \text{p}_1[\text{dom } f, \text{dom } g], g \cdot \text{p}_0[\text{dom } f, \text{dom } g] \rangle$

unfolding *ECC.prod-def* **by** *simp*

also have $\dots = f \cdot \text{p}_1[\text{dom } f, \text{dom } g]$

using *0 1 ECC.pr-tuple(1)* **by** *fastforce*

also have $\dots = (f \cdot \text{r}[\text{dom } f]) \cdot (\text{dom } f \otimes \text{t}[\text{dom } g])$

unfolding *pr₁-def*

using *comp-assoc* **by** *simp*

also have $\dots = (\text{r}[\text{cod } f] \cdot (f \otimes \mathcal{I})) \cdot (\text{dom } f \otimes \text{t}[\text{dom } g])$

using *0 runit-naturality* **by** *auto*

also have $\dots = \text{r}[\text{cod } f] \cdot (f \otimes \mathcal{I}) \cdot (\text{dom } f \otimes \text{t}[\text{dom } g])$

using *comp-assoc* **by** *simp*

also have $\dots = \text{r}[\text{cod } f] \cdot (\text{cod } f \otimes \text{t}[\text{cod } g]) \cdot (f \otimes g)$

using *0 interchange comp-arr-dom comp-cod-arr trm-naturality trm-simps(1)*

by *force*

also have $\dots = (\text{r}[\text{cod } f] \cdot (\text{cod } f \otimes \text{t}[\text{cod } g])) \cdot (f \otimes g)$

using *comp-assoc* **by** *simp*

also have $\dots = \text{p}_1[\text{cod } f, \text{cod } g] \cdot (f \otimes g)$

unfolding *pr₁-def* **by** *simp*

finally show *?thesis* **by** *blast*

qed

moreover have $\text{p}_0[\text{cod } f, \text{cod } g] \cdot \text{ECC.prod } f g = \text{p}_0[\text{cod } f, \text{cod } g] \cdot (f \otimes g)$

proof –

have $\text{p}_0[\text{cod } f, \text{cod } g] \cdot \text{ECC.prod } f g =$

$\text{p}_0[\text{cod } f, \text{cod } g] \cdot \langle f \cdot \text{p}_1[\text{dom } f, \text{dom } g], g \cdot \text{p}_0[\text{dom } f, \text{dom } g] \rangle$

```

    unfolding ECC.prod-def by simp
  also have ... =  $g \cdot \mathfrak{p}_0[\text{dom } f, \text{dom } g]$ 
    using 0 1 ECC.pr-tuple by fastforce
  also have ... =  $(g \cdot \mathfrak{l}[\text{dom } g]) \cdot (\mathfrak{t}[\text{dom } f] \otimes \text{dom } g)$ 
    unfolding pr0-def
    using comp-assoc by simp
  also have ... =  $(\mathfrak{l}[\text{cod } g] \cdot (\mathcal{I} \otimes g)) \cdot (\mathfrak{t}[\text{dom } f] \otimes \text{dom } g)$ 
    using 0 lunit-naturality by auto
  also have ... =  $\mathfrak{l}[\text{cod } g] \cdot (\mathcal{I} \otimes g) \cdot (\mathfrak{t}[\text{dom } f] \otimes \text{dom } g)$ 
    using comp-assoc by simp
  also have ... =  $\mathfrak{l}[\text{cod } g] \cdot (\mathfrak{t}[\text{cod } f] \otimes \text{cod } g) \cdot (f \otimes g)$ 
    using 0 interchange comp-arr-dom comp-cod-arr trm-naturality trm-simps(1)
    by force
  also have ... =  $(\mathfrak{l}[\text{cod } g] \cdot (\mathfrak{t}[\text{cod } f] \otimes \text{cod } g)) \cdot (f \otimes g)$ 
    using comp-assoc by simp
  also have ... =  $\mathfrak{p}_0[\text{cod } f, \text{cod } g] \cdot (f \otimes g)$ 
    unfolding pr0-def by simp
  finally show ?thesis by blast
qed
ultimately show ?thesis
  by (metis 0 1 ECC.pr-naturality(1-2) ECC.tuple-pr-arr ide-cod)
qed
qed
thus ?thesis by blast
qed

```

```

lemma Prod-eq-T:
shows ECC.Prod = T
proof
  fix fg
  show ECC.Prod fg = T fg
    using prod-eq-tensor
    by (cases CC.arr fg) auto
qed

```

```

lemma tuple-pr [simp]:
assumes ide a and ide b
shows  $\langle \mathfrak{p}_1[a, b], \mathfrak{p}_0[a, b] \rangle = a \otimes b$ 
  using assms prod-eq-tensor by simp

```

```

lemma tensor-expansion:
assumes arr f and arr g
shows  $f \otimes g = \langle f \cdot \mathfrak{p}_1[\text{dom } f, \text{dom } g], g \cdot \mathfrak{p}_0[\text{dom } f, \text{dom } g] \rangle$ 
  using assms
  by (metis ECC.prod-def prod-eq-tensor)

```

It is somewhat amazing that once the tensor product has been assumed to be a categorical product with the indicated projections, then the associators are forced to be those induced by the categorical product.

lemma *pr-assoc*:

assumes *ide a* **and** *ide b* **and** *ide c*

shows $\mathfrak{p}_1[a, b \otimes c] \cdot \mathfrak{a}[a, b, c] = \mathfrak{p}_1[a, b] \cdot \mathfrak{p}_1[a \otimes b, c]$

and $\mathfrak{p}_1[b, c] \cdot \mathfrak{p}_0[a, b \otimes c] \cdot \mathfrak{a}[a, b, c] = \mathfrak{p}_0[a, b] \cdot \mathfrak{p}_1[a \otimes b, c]$

and $\mathfrak{p}_0[b, c] \cdot \mathfrak{p}_0[a, b \otimes c] \cdot \mathfrak{a}[a, b, c] = \mathfrak{p}_0[a \otimes b, c]$

proof –

show $\mathfrak{p}_1[a, b \otimes c] \cdot \mathfrak{a}[a, b, c] = \mathfrak{p}_1[a, b] \cdot \mathfrak{p}_1[a \otimes b, c]$

proof –

have $\mathfrak{p}_1[a, b \otimes c] \cdot \mathfrak{a}[a, b, c] = (\mathfrak{r}[a] \cdot (a \otimes \iota \cdot (\mathfrak{t}[b] \otimes \mathfrak{t}[c]))) \cdot \mathfrak{a}[a, b, c]$

by (*metis ECC.trm-tensor ECC.unit-eq-trm arr-cod-iff-arr assms(2-3) comp-cod-arr dom-lunit ide-unity pr1-def prod-eq-tensor trm-naturality trm-one trm-simps(1) unitor-coincidence(1)*)

also have $\dots = (\mathfrak{r}[a] \cdot (a \otimes \iota) \cdot (a \otimes \mathfrak{t}[b] \otimes \mathfrak{t}[c])) \cdot \mathfrak{a}[a, b, c]$

using *assms interchange unit-in-hom-ax* **by** *auto*

also have $\dots = \mathfrak{r}[a] \cdot (a \otimes \iota) \cdot (a \otimes \mathfrak{t}[b] \otimes \mathfrak{t}[c]) \cdot \mathfrak{a}[a, b, c]$

using *comp-assoc* **by** *simp*

also have $\dots = \mathfrak{r}[a] \cdot (a \otimes \iota) \cdot \mathfrak{a}[a, \mathcal{I}, \mathcal{I}] \cdot ((a \otimes \mathfrak{t}[b]) \otimes \mathfrak{t}[c])$

using *assms assoc-naturality [of a t[b] t[c]]* **by** *force*

also have $\dots = \mathfrak{r}[a] \cdot (\mathfrak{r}[a] \otimes \mathcal{I}) \cdot ((a \otimes \mathfrak{t}[b]) \otimes \mathfrak{t}[c])$

using *assms runit-char comp-assoc* **by** *simp*

also have $\dots = \mathfrak{r}[a] \cdot (\mathfrak{p}_1[a, b] \otimes \mathfrak{t}[c])$

using *assms comp-arr-dom comp-cod-arr interchange [of r[a] a t[b] I t[c]]*

by (*metis ECC.pr-simps(4) pr1-def trm-simps(1) trm-simps(3)*)

also have $\dots = \mathfrak{r}[a] \cdot (\mathfrak{p}_1[a, b] \cdot (a \otimes b) \otimes \mathcal{I} \cdot \mathfrak{t}[c])$

using *assms comp-arr-dom comp-cod-arr*

by (*metis (no-types, lifting) ECC.pr-simps(4-5) prod-eq-tensor trm-simps(1,3)*)

also have $\dots = \mathfrak{r}[a] \cdot (\mathfrak{p}_1[a, b] \otimes \mathcal{I}) \cdot ((a \otimes b) \otimes \mathfrak{t}[c])$

using *assms interchange [of p1[a, b] a t[b] I t[c]]*

by (*metis (no-types, lifting) ECC.pr-simps(4-5) Prod-eq-T comp-arr-dom comp-cod-arr fst-conv snd-conv trm-simps(1,3)*)

also have $\dots = (\mathfrak{r}[a] \cdot (\mathfrak{p}_1[a, b] \otimes \mathcal{I})) \cdot ((a \otimes b) \otimes \mathfrak{t}[c])$

using *comp-assoc* **by** *simp*

also have $\dots = (\mathfrak{p}_1[a, b] \cdot \mathfrak{r}[a \otimes b]) \cdot ((a \otimes b) \otimes \mathfrak{t}[c])$

using *assms runit-naturality*

by (*metis (no-types, lifting) ECC.cod-pr1 ECC.pr-simps(4,5) prod-eq-tensor*)

also have $\dots = \mathfrak{p}_1[a, b] \cdot \mathfrak{p}_1[a \otimes b, c]$

using *pr1-def comp-assoc* **by** *simp*

finally show *?thesis* **by** *blast*

qed

show $\mathfrak{p}_1[b, c] \cdot \mathfrak{p}_0[a, b \otimes c] \cdot \mathfrak{a}[a, b, c] = \mathfrak{p}_0[a, b] \cdot \mathfrak{p}_1[a \otimes b, c]$

proof –

have $\mathfrak{p}_1[b, c] \cdot \mathfrak{p}_0[a, b \otimes c] \cdot \mathfrak{a}[a, b, c] =$

$\mathfrak{r}[b] \cdot (b \otimes \mathfrak{t}[c]) \cdot \mathfrak{l}[b \otimes c] \cdot \mathfrak{a}[\mathcal{I}, b, c] \cdot ((\mathfrak{t}[a] \otimes b) \otimes c)$

using *assms pr0-def pr1-def assoc-naturality [of t[a] b c] comp-assoc* **by** *auto*

also have $\dots = \mathfrak{r}[b] \cdot ((b \otimes \mathfrak{t}[c]) \cdot \mathfrak{l}[b \otimes c]) \cdot \mathfrak{a}[\mathcal{I}, b, c] \cdot ((\mathfrak{t}[a] \otimes b) \otimes c)$

using *comp-assoc* **by** *simp*

also have $\dots = \mathfrak{r}[b] \cdot (\mathfrak{l}[b \otimes \mathcal{I}] \cdot (\mathcal{I} \otimes b \otimes \mathfrak{t}[c])) \cdot \mathfrak{a}[\mathcal{I}, b, c] \cdot ((\mathfrak{t}[a] \otimes b) \otimes c)$

using *assms lunit-naturality [of b t[c]]* **by** *auto*

also have $\dots = \mathfrak{r}[b] \cdot \mathfrak{l}[b \otimes \mathcal{I}] \cdot ((\mathcal{I} \otimes b \otimes \mathfrak{t}[c]) \cdot \mathfrak{a}[\mathcal{I}, b, c]) \cdot ((\mathfrak{t}[a] \otimes b) \otimes c)$

```

    using comp-assoc by simp
  also have ... = r[b] · l[b ⊗ I] · (a[I, b, I] · ((I ⊗ b) ⊗ t[c])) · ((t[a] ⊗ b) ⊗ c)
    using assms assoc-naturality [of I b t[c]] by auto
  also have ... = r[b] · (l[b] ⊗ I) · ((I ⊗ b) ⊗ t[c]) · ((t[a] ⊗ b) ⊗ c)
    using assms lunit-tensor [of b I] comp-assoc
    by (metis ide-unity lunit-tensor')
  also have ... = r[b] · (l[b] ⊗ I) · ((t[a] ⊗ b) ⊗ I) · ((a ⊗ b) ⊗ t[c])
    using assms comp-arr-dom comp-cod-arr interchange by simp
  also have ... = (r[b] · (p₀[a, b] ⊗ I)) · ((a ⊗ b) ⊗ t[c])
    using assms pr₀-def ECC.pr-simps(1) R.preserves-comp comp-assoc by simp
  also have ... = (p₀[a, b] · r[a ⊗ b]) · ((a ⊗ b) ⊗ t[c])
    using assms pr₀-def runit-naturality [of p₀[a, b]] comp-assoc by simp
  also have ... = p₀[a, b] · p₁[a ⊗ b, c]
    using pr₀-def pr₁-def comp-assoc by simp
  finally show ?thesis by blast
qed
show p₀[b, c] · p₀[a, b ⊗ c] · a[a, b, c] = p₀[a ⊗ b, c]
proof -
  have p₀[b, c] · p₀[a, b ⊗ c] · a[a, b, c] =
    l[c] · (t[b] ⊗ c) · l[b ⊗ c] · (t[a] ⊗ b ⊗ c) · a[a, b, c]
    using pr₀-def comp-assoc by simp
  also have ... = l[c] · ((t[b] ⊗ c) · l[b ⊗ c]) · a[I, b, c] · ((t[a] ⊗ b) ⊗ c)
    using assms assoc-naturality [of t[a] b c] comp-assoc by simp
  also have ... = l[c] · (l[I ⊗ c] · (I ⊗ t[b] ⊗ c)) · a[I, b, c] · ((t[a] ⊗ b) ⊗ c)
    using assms lunit-naturality [of t[b] ⊗ c] by simp
  also have ... = l[c] · l[I ⊗ c] · (a[I, I, c] · ((I ⊗ t[b]) ⊗ c)) · ((t[a] ⊗ b) ⊗ c)
    using assms assoc-naturality [of I t[b] c] comp-assoc by simp
  also have ... = l[c] · (l[I ⊗ c] · a[I, I, c]) · ((I ⊗ t[b]) ⊗ c) · ((t[a] ⊗ b) ⊗ c)
    using comp-assoc by simp
  also have ... = l[c] · (ι ⊗ c) · ((I ⊗ t[b]) ⊗ c) · ((t[a] ⊗ b) ⊗ c)
    using assms lunit-tensor' unitor-coincidence(1) by simp
  also have ... = l[c] · (ι ⊗ c) · ((I ⊗ t[b]) · (t[a] ⊗ b) ⊗ c)
    using assms comp-arr-dom comp-cod-arr
    by (metis arr-tensor ide-char interchange trm-simps(1-3))
  also have ... = l[c] · (ι ⊗ c) · ((t[a] ⊗ t[b]) ⊗ c)
    using assms comp-arr-dom comp-cod-arr interchange by simp
  also have ... = l[c] · (ι · (t[a] ⊗ t[b]) ⊗ c)
    using assms interchange unit-in-hom-ax by auto
  also have ... = p₀[a ⊗ b, c]
  using assms pr₀-def ECC.trm-tensor category.comp-arr-dom category-axioms prod-eq-tensor
    trm-one unit-in-hom-ax unitor-coincidence(1)
    by fastforce
  finally show ?thesis by blast
qed
qed

```

lemma *assoc-agreement*:
assumes *ide a and ide b and ide c*
shows *ECC.assoc a b c = a[a, b, c]*

proof –
have $\mathfrak{p}_1[a, b \otimes c] \cdot ECC.assoc\ a\ b\ c = \mathfrak{p}_1[a, b \otimes c] \cdot a[a, b, c]$
using *assms* $ECC.pr-assoc(3)$ $pr-assoc(1)$ *prod-eq-tensor* **by** *force*
moreover have $\mathfrak{p}_0[a, b \otimes c] \cdot ECC.assoc\ a\ b\ c = \mathfrak{p}_0[a, b \otimes c] \cdot a[a, b, c]$
proof –
have $\mathfrak{p}_1[b, c] \cdot \mathfrak{p}_0[a, b \otimes c] \cdot ECC.assoc\ a\ b\ c = \mathfrak{p}_1[b, c] \cdot \mathfrak{p}_0[a, b \otimes c] \cdot a[a, b, c]$
using *assms* $ECC.pr-assoc(2)$ $pr-assoc(2)$ *prod-eq-tensor* **by** *force*
moreover have $\mathfrak{p}_0[b, c] \cdot \mathfrak{p}_0[a, b \otimes c] \cdot ECC.assoc\ a\ b\ c =$
 $\mathfrak{p}_0[b, c] \cdot \mathfrak{p}_0[a, b \otimes c] \cdot a[a, b, c]$
using *assms* *prod-eq-tensor* $ECC.pr-assoc(1)$ $pr-assoc(3)$ **by** *force*
ultimately show *?thesis*
using *assms* *prod-eq-tensor*
 $ECC.pr-joint-monic$
 $[of\ b\ c\ \mathfrak{p}_0[a, b \otimes c] \cdot ECC.assoc\ a\ b\ c\ \mathfrak{p}_0[a, b \otimes c] \cdot a[a, b, c]]$
by *fastforce*
qed
ultimately show *?thesis*
using *assms* *prod-eq-tensor*
 $ECC.pr-joint-monic\ [of\ a\ b \otimes c\ ECC.assoc\ a\ b\ c\ a[a, b, c]]$
by *fastforce*
qed

lemma *lunit-eq*:
assumes *ide a*
shows $\mathfrak{p}_0[\mathcal{I}, a] = l[a]$
by (*simp add: assms comp-arr-dom pr₀-def trm-one*)

lemma *runit-eq*:
assumes *ide a*
shows $\mathfrak{p}_1[a, \mathcal{I}] = r[a]$
by (*simp add: assms comp-arr-dom pr₁-def trm-one*)

lemma *lunit'-as-tuple*:
assumes *ide a*
shows *tuple t[a] a = lunit' a*
using $ECC.inverse-arrows-lunit$ *assms inverse-unique lunit-eq* **by** *fastforce*

lemma *runit'-as-tuple*:
assumes *ide a*
shows *tuple a t[a] = runit' a*
using $ECC.inverse-arrows-runit$ *assms inverse-unique runit-eq* **by** *fastforce*

interpretation *S*: *symmetry-functor C C ..*

interpretation *ToS*: *composite-functor CC.comp CC.comp C S.map T ..*

interpretation σ : *natural-transformation CC.comp C T ToS.map ECC. σ*

proof –
have $ECC.Prod' = ToS.map$
proof

```

fix fg
show ECC.Prod' fg = ToS.map fg
  using prod-eq-tensor
by (metis CC.arr-char ECC.prod-def ECC.tuple-ext S.map-def ToS.extensionality o-apply
seqE)
qed
thus natural-transformation CC.comp C T ToS.map ECC.σ
  using Prod-eq-T ECC.σ-naturalitytransformation by simp
qed

```

```

interpretation σ: natural-isomorphism CC.comp C T ToS.map ECC.σ
  using ECC.sym-inverse-arrows comp-arr-dom
  by unfold-locales auto

```

```

sublocale SMC: symmetric-monoidal-category C T α ι ECC.σ

```

```

proof

```

```

show  $\bigwedge a b. \llbracket \text{ide } a; \text{ ide } b \rrbracket \implies \text{inverse-arrows } (ECC.\sigma (a, b)) (ECC.\sigma (b, a))$ 
  using comp-arr-dom by auto
show  $\bigwedge a. \text{ide } a \implies \text{l}[a] \cdot ECC.\sigma (a, \mathcal{I}) = \text{r}[a]$ 
  using σ.naturality prod-eq-tensor
  by (metis (no-types, lifting) CC.arr-char ECC.prj-sym(1) R.preserves-ide
l-ide-simp ρ-ide-simp σ.preserves-reflects-arr comp-arr-ide fst-conv
ideD(1) ideD(3) ide-unity lunit-naturality pr0-def pr1-def runit-naturality
snd-conv trm-one)

```

```

show  $\bigwedge a b c. \llbracket \text{ide } a; \text{ ide } b; \text{ ide } c \rrbracket \implies$ 
   $\text{a}[b, c, a] \cdot ECC.\sigma (a, b \otimes c) \cdot \text{a}[a, b, c] =$ 
   $(b \otimes ECC.\sigma (a, c)) \cdot \text{a}[b, a, c] \cdot (ECC.\sigma (a, b) \otimes c)$ 

```

```

proof –

```

```

fix a b c

```

```

assume a: ide a and b: ide b and c: ide c

```

```

show  $\text{a}[b, c, a] \cdot ECC.\sigma (a, b \otimes c) \cdot \text{a}[a, b, c] =$ 
   $(b \otimes ECC.\sigma (a, c)) \cdot \text{a}[b, a, c] \cdot (ECC.\sigma (a, b) \otimes c)$ 

```

```

  using a b c prod-eq-tensor assoc-agreement comp-arr-dom ECC.sym-assoc-coherence [of
a b c]

```

```

  by simp

```

```

qed

```

```

qed

```

```

end

```

5.3 Elementary Cartesian Monoidal Category

```

locale elementary-cartesian-monoidal-category =
  elementary-monoidal-category C tensor unity lunit runit assoc
for C :: 'a comp (infixr <·> 55)
and tensor :: 'a  $\Rightarrow$  'a  $\Rightarrow$  'a (infixr <⊗> 53)
and unity :: 'a (⟨I⟩)
and lunit :: 'a  $\Rightarrow$  'a (⟨l[-]⟩)
and runit :: 'a  $\Rightarrow$  'a (⟨r[-]⟩)

```

```

and assoc :: 'a ⇒ 'a ⇒ 'a ⇒ 'a (⟨a[-, -, -]⟩)
and trm :: 'a ⇒ 'a (⟨t[-]⟩)
and dup :: 'a ⇒ 'a (⟨d[-]⟩) +
assumes trm-in-hom: ide a ⇒ «t[a] : a → I»
and trm-unity: t[I] = I
and trm-naturality: arr f ⇒ t[cod f] · f = t[dom f]
and dup-in-hom [intro]: ide a ⇒ «d[a] : a → a ⊗ a»
and dup-naturality: arr f ⇒ d[cod f] · f = (f ⊗ f) · d[dom f]
and prj0-dup: ide a ⇒ r[a] · (a ⊗ t[a]) · d[a] = a
and prj1-dup: ide a ⇒ l[a] · (t[a] ⊗ a) · d[a] = a
and tuple-prj: [ ide a; ide b ] ⇒ (r[a] · (a ⊗ t[b]) ⊗ l[b] · (t[a] ⊗ b)) · d[a ⊗ b] = a ⊗ b

```

```

context cartesian-monoidal-category
begin

```

```

  interpretation elementary-category-with-terminal-object C I the-trm
  using extends-to-elementary-category-with-terminal-objectCMC by blast

```

```

  interpretation elementary-monoidal-category C tensor unity lunit runit assoc
  using induces-elementary-monoidal-category by simp

```

```

  interpretation elementary-cartesian-monoidal-category C
  tensor unity lunit runit assoc the-trm dup
  using ECC.trm-one ECC.trm-naturality ECC.tuple-in-hom' prod-eq-tensor ECC.dup-naturality
  in-homI
  ECC.comp-runit-term-dup runit-eq ECC.comp-lunit-term-dup lunit-eq ECC.tuple-expansion
  comp-cod-arr
  apply unfold-locales
  apply auto

```

```

  proof –
  fix a b
  assume a: ide a and b: ide b
  show (r[a] · (a ⊗ t[b]) ⊗ l[b] · (t[a] ⊗ b)) · d[a ⊗ b] = a ⊗ b
  using a b ECC.tuple-pr pr0-def pr1-def prod-eq-tensor
  by (metis ECC.pr-simps(5) ECC.span-pr ECC.tuple-expansion)
  qed

```

```

  lemma induces-elementary-cartesian-monoidal-categoryCMC:
  shows elementary-cartesian-monoidal-category C tensor I lunit runit assoc the-trm dup
  ..

```

```

end

```

```

context elementary-cartesian-monoidal-category
begin

```

```

  lemma trm-simps [simp]:
  assumes ide a
  shows arr t[a] and dom t[a] = a and cod t[a] = I

```

```

using assms trm-in-hom by auto

lemma dup-simps [simp]:
assumes ide a
shows arr d[a] and dom d[a] = a and cod d[a] = a ⊗ a
using assms dup-in-hom by auto

interpretation elementary-category-with-terminal-object C I trm
apply unfold-locales
apply auto
by (metis comp-cod-arr in-homE trm-naturality trm-unity)

lemma is-elementary-category-with-terminal-object:
shows elementary-category-with-terminal-object C I trm
..

interpretation MC: monoidal-category C T α ι
using induces-monoidal-category by auto

interpretation ECBP: elementary-category-with-binary-products C
      ⟨λa b. l[b] · (t[a] ⊗ b)⟩ ⟨λa b. r[a] · (a ⊗ t[b])⟩

proof –
let ?pr0 = λa b. l[b] · (t[a] ⊗ b)
let ?pr1 = λa b. r[a] · (a ⊗ t[b])
show elementary-category-with-binary-products C ?pr0 ?pr1
proof
fix a b
assume a: ide a and b: ide b
show 0: cod (?pr0 a b) = b
by (metis a arr-tensor b cod-comp cod-tensor ide-char in-homE lunit-in-hom
      seqI trm-simps(1,3))
show 1: cod (?pr1 a b) = a
by (metis a arr-tensor b cod-comp cod-tensor ideD(1,3) in-homE runit-in-hom
      seqI trm-simps(1,3))
show span (?pr1 a b) (?pr0 a b)
by (metis 0 1 a arr-cod-iff-arr b dom-cod dom-comp dom-tensor ideD(1) trm-simps(1–2))
next
fix f g
assume fg: span f g
show ∃!l. ?pr1 (cod f) (cod g) · l = f ∧ ?pr0 (cod f) (cod g) · l = g
proof
show 1: ?pr1 (cod f) (cod g) · (f ⊗ g) · d[dom f] = f ∧
      ?pr0 (cod f) (cod g) · (f ⊗ g) · d[dom f] = g
proof
show ?pr1 (cod f) (cod g) · (f ⊗ g) · d[dom f] = f
proof –
have ?pr1 (cod f) (cod g) · (f ⊗ g) · d[dom f] =
      MC.runit (cod f) · (MC.tensor (cod f) t[cod g] · (f ⊗ g)) · d[dom f]

```

by (*simp add: fg comp-assoc runit-agreement*)
 also have ... = $MC.runit (cod f) \cdot (MC.tensor f \mathcal{I} \cdot (dom f \otimes t[dom g])) \cdot d[dom f]$
 using *fg*
 by (*simp add: comp-arr-dom comp-cod-arr interchange trm-naturality*)
 also have ... = $(MC.runit (cod f) \cdot MC.tensor f \mathcal{I}) \cdot (dom f \otimes t[dom g]) \cdot d[dom f]$
 using *comp-assoc by simp*
 also have ... = $f \cdot ?pr_1 (dom f) (dom g) \cdot d[dom f]$
 using *MC.runit-naturality \mathcal{I}-agreement fg comp-assoc runit-agreement by force*
 also have ... = f
 using *fg comp-arr-dom comp-assoc prj0-dup runit-agreement by fastforce*
 finally show *?thesis by blast*
 qed
 show $?pr_0 (cod f) (cod g) \cdot (f \otimes g) \cdot d[dom f] = g$
 proof -
 have $?pr_0 (cod f) (cod g) \cdot (f \otimes g) \cdot d[dom f] =$
 $MC.lunit (cod g) \cdot (MC.tensor t[cod f] (cod g) \cdot (f \otimes g)) \cdot d[dom f]$
 by (*simp add: fg comp-assoc lunit-agreement*)
 also have ... = $MC.lunit (cod g) \cdot (MC.tensor \mathcal{I} g \cdot (t[dom f] \otimes dom g)) \cdot d[dom f]$
 using *fg*
 by (*simp add: comp-arr-dom comp-cod-arr interchange trm-naturality*)
 also have ... = $(MC.lunit (cod g) \cdot MC.tensor \mathcal{I} g) \cdot (t[dom f] \otimes dom g) \cdot d[dom f]$
 using *comp-assoc by simp*
 also have ... = $g \cdot ?pr_0 (dom f) (dom g) \cdot d[dom f]$
 using *MC.lunit-naturality \mathcal{I}-agreement fg comp-assoc lunit-agreement by force*
 also have ... = g
 using *fg comp-arr-dom comp-assoc prj1-dup lunit-agreement by fastforce*
 finally show *?thesis by blast*
 qed
 qed
 fix l
 assume $l: ?pr_1 (cod f) (cod g) \cdot l = f \wedge ?pr_0 (cod f) (cod g) \cdot l = g$
 show $l = (f \otimes g) \cdot d[dom f]$
 proof -
 have $2: \langle l : dom f \rightarrow cod f \otimes cod g \rangle$
 by (*metis 1 arr-iff-in-hom cod-comp cod-tensor dom-comp fg l seqE*)
 have $l = ((?pr_1 (cod f) (cod g) \otimes ?pr_0 (cod f) (cod g)) \cdot d[cod f \otimes cod g]) \cdot l$
 using *fg 2 tuple-prj [of cod f cod g] lunit-agreement runit-agreement comp-cod-arr*
 by *auto*
 also have ... = $(?pr_1 (cod f) (cod g) \otimes ?pr_0 (cod f) (cod g)) \cdot d[cod f \otimes cod g] \cdot l$
 using *comp-assoc by simp*
 also have ... = $((?pr_1 (cod f) (cod g) \otimes ?pr_0 (cod f) (cod g)) \cdot (l \otimes l)) \cdot d[dom f]$
 using *2 dup-naturality [of l] comp-assoc by auto*
 also have ... = $(f \otimes g) \cdot d[dom f]$
 using *fg l interchange [of ?pr_1 (cod f) (cod g) l ?pr_0 (cod f) (cod g) l] by simp*
 finally show *?thesis by blast*
 qed
 qed
 qed
 qed

```

lemma induces-elementary-category-with-binary-productsECMC:
shows elementary-category-with-binary-products C
  (( $\lambda a b. l[b] \cdot (t[a] \otimes b)$ ) ( $\lambda a b. r[a] \cdot (a \otimes t[b])$ ))
  ..

sublocale cartesian-monoidal-category C T  $\alpha$   $\iota$ 
proof
  show terminal MC.unity
  by (simp add:  $\mathcal{I}$ -agreement terminal-one)
  show  $\bigwedge a b t_a t_b. \llbracket \text{ide } a; \text{ ide } b; \langle t_a : a \rightarrow MC.unity \rangle; \langle t_b : b \rightarrow MC.unity \rangle \rrbracket \implies$ 
    has-as-binary-product a b
    (MC.runit a · MC.tensor a t_b) (MC.lunit b · MC.tensor t_a b)
  by (metis ECBP.has-as-binary-product T-simp  $\mathcal{I}$ -agreement arrI ideD(1)
    lunit-agreement runit-agreement trm-eqI)
qed

lemma induces-cartesian-monoidal-categoryECMC:
shows cartesian-monoidal-category C T  $\alpha$   $\iota$ 
  ..

end

locale diagonal-functor =
  C: category C +
  CC: product-category C C
for C :: 'a comp
begin

  abbreviation map
  where map f  $\equiv$  if C.arr f then (f, f) else CC.null

  lemma is-functor:
  shows functor C CC.comp map
  using map-def by unfold-locales auto

  sublocale functor C CC.comp map
  using is-functor by simp

end

context cartesian-monoidal-category
begin

  sublocale  $\Delta$ : diagonal-functor C ..
  interpretation To $\Delta$ : composite-functor C CC.comp C  $\Delta$ .map T ..

  sublocale  $\delta$ : natural-transformation C C map  $\langle T \circ \Delta.map \rangle$  dup

```

```

proof
  show  $\bigwedge f. \neg \text{arr } f \implies \text{d}[f] = \text{null}$ 
    using ECC.tuple-ext by blast
  show  $\bigwedge f. \text{arr } f \implies \text{arr } \text{d}[f]$ 
    using dup-def by simp
  show  $\bigwedge f. \text{arr } f \implies \text{To}\Delta.\text{map } f \cdot \text{d}[\text{dom } f] = \text{d}[f]$ 
    using ECC.tuple-expansion prod-eq-tensor by force
  show  $\bigwedge f. \text{arr } f \implies \text{d}[\text{cod } f] \cdot \text{map } f = \text{d}[f]$ 
    by (simp add: comp-cod-arr dup-def)
qed

```

end

5.4 Cartesian Monoidal Category from Cartesian Category

A cartesian category extends to a cartesian monoidal category by using the product structure to obtain the various canonical maps.

```

context elementary-cartesian-category
begin

  interpretation CC: product-category C C ..
  interpretation CCC: product-category C CC.comp ..
  interpretation T: binary-functor C C C Prod
    using binary-functor-Prod by simp
  interpretation T: binary-endofunctor C Prod ..
  interpretation ToTC: functor CCC.comp C T.ToTC
    using T.functor-ToTC by auto
  interpretation ToCT: functor CCC.comp C T.ToCT
    using T.functor-ToCT by auto

  interpretation  $\alpha$ : natural-isomorphism CCC.comp C T.ToTC T.ToCT  $\alpha$ 
    using  $\alpha$ -naturalityisomorphism by blast

  interpretation L: functor C C  $\langle \lambda f. \text{Prod } (\text{cod } \iota, f) \rangle$ 
    using unit-is-terminal-arr T.fixing-ide-gives-functor-1 by simp
  interpretation L: endofunctor C  $\langle \lambda f. \text{Prod } (\text{cod } \iota, f) \rangle ..$ 
  interpretation l: transformation-by-components C C
     $\langle \lambda f. \text{Prod } (\text{cod } \iota, f) \rangle \text{map } \langle \lambda a. \text{pr0 } (\text{cod } \iota) a \rangle$ 
    using unit-is-terminal-arr
    by unfold-locales auto
  interpretation l: natural-isomorphism C C  $\langle \lambda f. \text{Prod } (\text{cod } \iota, f) \rangle \text{map } \text{l.map}$ 
    using l.map-simp-ide inverse-arrows-lunit ide-one
    by unfold-locales auto
  interpretation L: equivalence-functor C C  $\langle \lambda f. \text{Prod } (\text{cod } \iota, f) \rangle$ 
    using l.natural-isomorphism-axioms naturally-isomorphic-def
    L.isomorphic-to-identity-is-equivalence
    by blast

```

interpretation R : functor $C C \langle \lambda f. \text{Prod } (f, \text{cod } \iota) \rangle$
using *unit-is-terminal-arr* *T.fixing-ide-gives-functor-2* **by** *simp*

interpretation R : endofunctor $C \langle \lambda f. \text{Prod } (f, \text{cod } \iota) \rangle$..

interpretation ϱ : transformation-by-components $C C$
 $\langle \lambda f. \text{Prod } (f, \text{cod } \iota) \rangle \text{ map } \langle \lambda a. \mathfrak{p}_1[a, \text{cod } \iota] \rangle$
using *unit-is-terminal-arr*
by *unfold-locales auto*

interpretation ϱ : natural-isomorphism $C C \langle \lambda f. \text{Prod } (f, \text{cod } \iota) \rangle \text{ map } \varrho.\text{map}$
using *$\varrho.\text{map-simp-ide}$* *inverse-arrows-runit* *ide-one*
by *unfold-locales auto*

interpretation R : equivalence-functor $C C \langle \lambda f. \text{Prod } (f, \text{cod } \iota) \rangle$
using *$\varrho.\text{natural-isomorphism-axioms}$* *naturally-isomorphic-def*
 $R.\text{isomorphic-to-identity-is-equivalence}$
by *blast*

interpretation MC : monoidal-category $C \text{Prod } \alpha \iota$
using *ide-one* *ι -is-iso* *pentagon* *comp-assoc* *α -simp-ide* *comp-cod-arr*
by *unfold-locales auto*

lemma *induces-monoidal-category_{ECC}*:
shows *monoidal-category* $C \text{Prod } \alpha \iota$
 ..

lemma *unity-agreement*:
shows $MC.\text{unity} = \mathbf{1}$
using *ide-one* **by** *simp*

lemma *assoc-agreement*:
assumes *ide a* **and** *ide b* **and** *ide c*
shows $MC.\text{assoc } a b c = a[a, b, c]$
using *assms* *assoc-def* *α -simp-ide* **by** *auto*

lemma *assoc'-agreement*:
assumes *ide a* **and** *ide b* **and** *ide c*
shows $MC.\text{assoc}' a b c = a^{-1}[a, b, c]$
using *assms* *inverse-arrows-assoc* *inverse-unique* *α -simp-ide* **by** *auto*

lemma *runit-char-eqn*:
assumes *ide a*
shows $r[a] \otimes \mathbf{1} = (a \otimes \iota) \cdot a[a, \mathbf{1}, \mathbf{1}]$
using *assms* *ide-one* *assoc-def* *comp-assoc* *prod-tuple* *comp-cod-arr*
by (*intro* *pr-joint-monic* [*of a* $\mathbf{1}$ $r[a] \otimes \mathbf{1}$ $(a \otimes \iota) \cdot a[a, \mathbf{1}, \mathbf{1}]$]) *auto*

lemma *runit-agreement*:
assumes *ide a*
shows $MC.\text{runit } a = r[a]$
using *assms* *unity-agreement* *assoc-agreement* *MC.runit-char(2)* *runit-char-eqn* *ide-one*
by (*metis* (*no-types*, *lifting*) *MC.runit-eqI* *fst-conv* *runit-in-hom* *snd-conv*)

lemma *lunit-char-eqn*:
assumes *ide a*
shows $\mathbf{1} \otimes l[a] = (\iota \otimes a) \cdot a^{-1}[\mathbf{1}, \mathbf{1}, a]$
proof (*intro pr-joint-monic [of $\mathbf{1} a \mathbf{1} \otimes l[a] (\iota \otimes a) \cdot a^{-1}[\mathbf{1}, \mathbf{1}, a]$]*)
 show *ide a* **by fact**
 show *ide 1*
 using *ide-one* **by simp**
 show *seq l[a] ($\mathbf{1} \otimes l[a]$)*
 using *assms ide-one* **by simp**
 show $l[a] \cdot (\mathbf{1} \otimes l[a]) = l[a] \cdot (\iota \otimes a) \cdot a^{-1}[\mathbf{1}, \mathbf{1}, a]$
 using *assms ide-one assoc'-def comp-assoc prod-tuple comp-cod-arr* **by simp**
 show $p_1[\mathbf{1}, a] \cdot \text{prod } \mathbf{1} (lunit\ a) = p_1[\mathbf{1}, a] \cdot \text{prod } \iota\ a \cdot \text{assoc}'\ \mathbf{1}\ \mathbf{1}\ a$
 using *assms ide-one assoc'-def comp-cod-arr prod-tuple pr-naturality*
 apply simp
 by (*metis (full-types) cod-pr0 cod-pr1 elementary-category-with-binary-products.ide-prod elementary-category-with-binary-products-axioms pr-simps(1-2,4-5) trm-naturality trm-one*)
qed

lemma *lunit-agreement*:
assumes *ide a*
shows $MC.lunit\ a = l[a]$
 by (*metis (no-types, lifting) MC.lunit-eqI assms assoc'-agreement fst-conv ide-one lunit-char-eqn lunit-in-hom snd-conv unity-agreement*)

interpretation *CMC*: *cartesian-monoidal-category C Prod α ι*
proof

show *terminal MC.unity*
 by (*simp add: terminal-one unity-agreement*)
 fix *a b t_a t_b*
 assume *a: ide a and b: ide b*
 and *t_a: «t_a : a → MC.unity» and t_b: «t_b : b → MC.unity»*
 have $0: p_0[a, b] = MC.lunit\ b \cdot MC.tensor\ t[a]\ b$
 by (*metis (no-types, lifting) a b ide-char cod-pr0 comp-cod-arr lunit-agreement pr-naturality(1) pr-simps(1) prod.sel(1-2) trm-simps(1-3)*)
 have $1: p_1[a, b] = MC.runit\ a \cdot MC.tensor\ a\ t[b]$
 by (*metis (no-types, lifting) a b cod-pr1 comp-cod-arr ide-char pr-naturality(2) pr-simps(4) prod.sel(1-2) runit-agreement trm-simps(1-3)*)
 have $2: t[a] = t_a \wedge t[b] = t_b$
 using *a b t_a t_b terminal-arr-unique trm-eqI unity-agreement* **by metis**
 show *has-as-binary-product a b (MC.runit a · MC.tensor a t_b) (MC.lunit b · MC.tensor t_a b)*
 using *a b 0 1 2 has-as-binary-product* **by force**
qed

lemma *extends-to-cartesian-monoidal-category_{ECC}*:
shows *cartesian-monoidal-category C Prod α ι*
 ..

lemma *trm-agreement*:
assumes *ide a*
shows $CMC.the-trm\ a = t[a]$
by (*metis* *assms* $CMC.extends-to-elementary-category-with-terminal-object_{CMC}$
elementary-category-with-terminal-object.trm-eqI *trm-in-hom* *unity-agreement*)

lemma *pr-agreement*:
assumes *ide a* **and** *ide b*
shows $CMC.pr_0\ a\ b = p_0[a, b]$ **and** $CMC.pr_1\ a\ b = p_1[a, b]$
proof –
show $CMC.pr_0\ a\ b = p_0[a, b]$
unfolding $CMC.pr_0-def$
using *assms*(1–2) *lunit-agreement* *pr-expansion*(1) *trm-agreement* **by** *auto*
show $CMC.pr_1\ a\ b = p_1[a, b]$
unfolding $CMC.pr_1-def$
using *assms*(1–2) *pr-expansion*(2) *runit-agreement* *trm-agreement* **by** *force*
qed

lemma *dup-agreement*:
assumes *ide a*
shows $CMC.dup\ a = d[a]$
by (*metis* (*no-types*, *lifting*) $CMC.ECC.tuple-eqI$ *assms* *ideD*(1) *pr-agreement*(1–2) *pr-dup*(1–2))

end

5.5 Cartesian Monoidal Category from Elementary Cartesian Category

context *elementary-cartesian-category*
begin

interpretation *MC*: *monoidal-category* $C\ Prod\ \alpha\ \iota$
using *induces-monoidal-category_{ECC}* **by** *blast*

lemma *triangle*:
assumes *ide a* **and** *ide b*
shows $(a \otimes l[b]) \cdot a[a, \mathbf{1}, b] = r[a] \otimes b$
using *assms* $MC.triangle$ [*of a b*] *assoc-agreement* *ide-one* *lunit-agreement*
runit-agreement *unity-agreement* *fst-conv* *snd-conv*
by (*metis* (*no-types*, *lifting*))

lemma *induces-elementary-cartesian-monoidal-category_{ECC}*:
shows *elementary-cartesian-monoidal-category* (\cdot) *prod* $\mathbf{1}$ *lunit* *runit* *assoc* *trm* *dup*
using *ide-one* *inverse-arrows-lunit* *inverse-arrows-runit* *inverse-arrows-assoc*
interchange *lunit-naturality* *runit-naturality* *assoc-naturality*
triangle *pentagon* *comp-assoc* *trm-one* *trm-naturality*

```

      in-homI prod-tuple isoI arr-dom MC.tensor-in-homI comp-arr-dom comp-cod-arr
apply unfold-locales
      apply simp-all
      apply blast
      apply blast
      by meson

end

context cartesian-category
begin

  interpretation ECC: elementary-cartesian-category C
      some-pr0 some-pr1 some-terminal some-terminator
  using extends-to-elementary-cartesian-category by simp

  lemma extends-to-cartesian-monoidal-categoryCC:
  shows cartesian-monoidal-category C ECC.Prod ECC.α ECC.ι
  using ECC.extends-to-cartesian-monoidal-categoryECC by blast

end

end

```

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